NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

OPTIMIZING THE LONG-TERM CAPACITY EXPANSION AND PROTECTION OF IRAQI OIL INFRASTRUCTURE

by

Patrick S. Brown

September 2005

First Thesis Advisor:	Gerald G. Brown
Second Thesis Advisor:	Curtis L. Blais
Second Reader:	Daniel A. Nussbaum

Approved for public release, distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2005	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE: Optimizing the Long-Term Capacity Expansion and Protection of Iraqi Oil Infrastructure

5. FUNDING NUMBERS

6. AUTHOR(S) Patrick S. Brown

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release, distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (maximum 200 words)

We introduce a tri-level defender-attacker-defender optimization model that prescribes how Iraq's oil infrastructure can, over time, be expanded, protected, and operated, even in the face of insurgent attacks. The outer-most defender model is a mixed-integer program that, given a set of anticipated insurgent attacks, specifies a quarterly capital expansion, defense, and operation plan to maximize oil exports over a decade-long planning horizon. The intermediate attacker model, observing the outer defender plans, is a mixed integer program that re-optimizes insurgent attacks to minimize export flow. The inner-most defender model is a linear program that re-directs flow in response to insurgent damage. We use open-source descriptions of current Iraqi oil infrastructure and reasonable estimates of the costs to expand capacity and/or defend operating assets, and reduce vulnerability to attacks. We solve this tri-level model by converting it into an equivalent bi-level one, and applying decomposition. For a range of scenarios, we determine the best allocation of effort between improving oil export infrastructure, and defending it.

14. SUBJECT TERMS
DIAMOND, Oil Infrastructure, Oil Pipeline, Capital Allocation and Expansion, Iraq, Tri-level Defender-Attacker-Defender Model, Cost Estimation, Mixed Integer Programming

15. NUMBER OF PAGES 139

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release, distribution is unlimited

OPTIMIZING THE LONG-TERM CAPACITY EXPANSION AND PROTECTION OF IRAQI OIL INFRASTRUCTURE

Patrick S. Brown
Lieutenant Commander, United States Navy
B.S., University of Idaho, 1991

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
September 2005

Author: Patrick S. Brown

Approved by: Gerald G. Brown
Thesis Advisor

Curtis L. Blais
Co-Adviser

Daniel A. Nussbaum
Second Reader

James N. Eagle
Chairman, Department of Operations Research

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

We introduce a tri-level defender-attacker-defender optimization model that prescribes how Iraq's oil infrastructure can, over time, be expanded, protected, and operated, even in the face of insurgent attacks. The outer-most defender model is a mixed-integer program that, given a set of anticipated insurgent attacks, specifies a quarterly capital expansion, defense, and operation plan to maximize oil exports over a decade-long planning horizon. The intermediate attacker model, observing the outer defender plans, is a mixed integer program that re-optimizes insurgent attacks to minimize export flow. The inner-most defender model is a linear program that re-directs flow in response to insurgent damage. We use open-source descriptions of current Iraqi oil infrastructure and reasonable estimates of the costs to expand capacity and/or defend operating assets, and reduce vulnerability to attacks. We solve this tri-level model by converting it into an equivalent bi-level one, and applying decomposition. For a range of scenarios, we determine the best allocation of effort between improving oil export infrastructure, and defending it.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF KEYWORDS, SYMBOLS, ACRONYMS AND ABBREVIATIONS

ACF	Area cost factor
bbd	Barrel(s) of crude oil per day
bbl	Barrel(s) of crude oil
BTC	Baku-Tbilisi-Ceyhan pipeline
CI	Confidence interval
d	Duration (in quarters)
Diam	Diameter
DMSO	Defense Modeling and Simulation Office
EIA	Energy Information Agency
ftUS	U.S. standard feet
FY	Fiscal year
gpm	Gallons per minute
IAGS	Institute for the Analysis of Global Security
IPC	Iraq Petroleum Company (defunct)
kbbd	Thousands of barrel(s) of crude oil per day
kbbl	Thousands of barrel(s) of crude oil
km	Kilometer
lat	Latitude
long	Longitude
mbbd	Millions of barrel(s) of crude oil per day
mbbl	Millions of barrel(s) of crude oil

mi	U.S. statute mile
NCAD	Navy Cost Analysis Division
NIMA	National Imagery and Mapping Agency
nm	nautical mile
NOC	Northern Oil Company (Iraq)
OPEC	Organization of Petroleum Exporting Countries
ord(q)	The ordinal value of quarter q
PI	Prediction interval
P/S	Pump station
qtrs	Quarters
SOC	Southern Oil Company (Iraq)
USACE	United States Army Corps of Engineers
wp	Waypoint
$/LF	Cost per U.S. standard linear foot
$M	Millions of dollars

ACKNOWLEDGMENTS

No one person ever writes a thesis. One individual may write the manuscript, but the concepts behind it are hammered out through years of study and consultation. A chance article or the work of a colleague sometimes strikes a nerve and stimulates the beginning of an idea and over time that idea evolves until final fruition.

This research is no different and it is certainly a collaboration of support and effort on the part of many people. First and foremost, I would thank my wife Deanna and my two children Emma and Gavin who have clearly given freely of their precious time to enable me to produce this research. One can only hope that somewhere in the master plan of my career we will get all those days back in spades. Thanks also to Distinguished Professor Jerry Brown, my thesis advisor, who demonstrated that great things can still be accomplished remotely using only a computer and a high-speed internet connection. I only wish that the Navy as a whole were as receptive to telecommuting as you have been because then the next three years in Washington D.C. would probably seem like a cake walk without the daily forty-five minute commute to look forward to. I want to thank Dr. Dan Nussbaum for his continual feedback on developing the various cost estimates used throughout this research. The numbers may be completely out to lunch but at least we know how we got them. Lastly, I want to thank Curt Blais from the MOVES Institute for sponsoring my experience tour and helping me frame this thesis into a meaningful scenario.

All together this has been an ambitious project. We all knew from the beginning that there was a lot of ground to cover. So thank you to everyone for answering my many questions and seeing this work through to completion.

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

Iraq has oil and natural gas that are by volume second only to its neighbor Saudi Arabia. Still, despite decades of production, only a small portion of Iraq's true oil-producing potential has ever been tapped and remained functioning. The leaders in Iraq know this and recognize that their country's future growth and prosperity hinge on developing and protecting their oil industry because roughly 95% of their foreign exchange earnings are generated from oil. The insurgents know this as well and are equally determined to undermine the government and bring about economic collapse by hobbling the nation's most profitable industry.

Since the beginning of Operation Iraqi Freedom, Iraq has sustained a reported 7 to 12 billion dollars in damages to its oil infrastructure and loss of revenues as a result of 257 attacks. These types of attacks are particularly troublesome because without efficient and reliable oil production – Iraq's principal resource – the newly-established government cannot generate the funds needed to repair damaged infrastructure. It also cannot attract outside capital to fund long-term improvements to the pipeline network or modernize its refineries to support domestic fuel requirements.

To provide a better understanding of the resiliency of the current Iraqi oil network and to explore options for improving it, this thesis seeks a multi-year capacity expansion and investment plan for Iraq's crude oil delivery system that allocates funds between increasing capacity and defense of completed infrastructure. Our goal is to maximize the daily volume of crude oil exported from Iraq for sale.

We accomplish this objective by introducing a tri-level defender-attacker-defender optimization model that prescribes how Iraq's oil infrastructure can, over time, be expanded, protected, and operated, even in the face of insurgent attacks. The outer-most defender model is a mixed-integer program that, given a set of anticipated insurgent attacks, specifies a quarterly capital expansion, defense, and operation plan to maximize oil exports over a decade-long planning horizon. The intermediate attacker model, observing the outer defender plans, is a mixed integer program that re-optimizes insurgent attacks to minimize export flow. The inner-most defender model is a linear

program that re-directs flow in response to insurgent damage. We use open-source descriptions of current Iraqi oil infrastructure and reasonable estimates of the costs to expand capacity and/or defend operating assets, and reduce vulnerability to attacks. We solve this tri-level model by converting it into an equivalent bi-level one, and applying decomposition. For a range of scenarios, we determine the best allocation of effort between improving oil export infrastructure, and defending it.

One distinguishing feature of the tri-level defender-attacker-defender model is that we formally represent our construction projects as being so large and costly that we cannot expect to hide our plans. We anticipate that insurgents will have full prior knowledge of our construction and defense strategy, and will carry out optimal attacks to the best of their ability on our vulnerable infrastructure to minimize our capacity to pump crude oil out of Iraq.

The results of our tri-level model indicate that significant improvements in export capacity are possible despite an ongoing insurgent campaign to hinder the flow of oil. Five different scenarios are considered. The first is a baseline scenario in which moderate attacks are allowed. The next two are escalations on the baseline scenario in which insurgents are allowed more attacks over the forty-quarter planning horizon, as well as multiple waves of attacks against the same targets (i.e. the defender doesn't learn from previous attacks and defend better). The final two scenarios explore the effect on oil exports if the construction and defense costs are actually 50% higher than baseline.

All five scenarios indicate that defensive measures are very important to limit the effects of the insurgent attacks. While each scenario is able to achieve over 6 million barrels per day in export capacity over the next 10 years, the scenario in which defense costs are the highest results in the most drastic decrease in total flow. However, defenses alone have their limitations. Unconstrained attacks against a finite infrastructure inevitably lead to decreases in exports. Defending critical infrastructure, therefore, requires striking a balance between adding redundancies and improving defensive measures.

I. INTRODUCTION

Formula for success: Rise early, work hard, strike oil.

Jean Paul Getty (1892-1976),
American Industrialist and Founder of the Getty Oil Company

A. MOTIVATION

Iraq has oil and natural gas that are by volume second only to its neighbor Saudi Arabia. Still, despite decades of production, only a small portion of Iraq's true oil-producing potential has ever been tapped and remained functioning. The leaders in Iraq know this and recognize that their country's future growth and prosperity hinge on developing and protecting the industry responsible for roughly 95% of its foreign exchange earnings. Insurgents know this as well and are equally determined to undermine the government and bring about economic collapse by hobbling the nation's most profitable industry.

Despite this clear dependence between oil exports and the economy, Iraq's enormous debt and the multitude of other high priority social needs have prevented any real significant investment in any one area. As a result, Iraq's infrastructure has languished for over a decade, its pipelines suffer daily attacks and looting, and its oil fields continue to post steady declines in production. In truth, Iraq has neglected its lifeblood industry for far too long and requires a capital expansion and security plan - as well as the financial commitments to execute it. This thesis is a first attempt at that plan and utilizes a three-level approach to determining the best combination of new construction, upgrades and defense of the Iraqi crude oil distribution network. All flow capacities, configurations, and costs are estimated representations of the current and future Iraqi crude oil distribution system. We focus on the distribution of crude oil for export, rather than its downstream processing and refining systems. We also rely on the assumption that technical issues involving oil extraction (i.e. water cut, damage from oil

re-injection, etc.) are resolved and that sufficient flows are attainable at the oil fields to meet published pipeline capacities.

B. BACKGROUND

World demand for oil currently stands at approximately 79.5 million barrels per day (mbbd) [McKillop, 2004] and continues to grow. The Persian Gulf countries, collectively, supply upwards of 27 percent of this demand (including 22 percent of U.S. imports) and possess approximately two thirds of the world's proven reserves.

This region plays a key role in sustaining a healthy world energy balance, above and beyond the obvious realities of supply and demand. The stable flow of oil to the largest industrial countries of the world is critical to their economies and industry. Preserving a "surplus" production capacity within the major oil producing regions is therefore in the interest of all nations and serves as a buffer against unexpected economic downturns and regional conflicts. At present, the only Persian Gulf nation with sustainable excess capacity is Saudi Arabia with approximately 1.0 to 1.5 mbbd and an estimated 1.2 trillion barrels in proven oil reserves [Kennedy, 2004]. Iraq, by comparison, has the world's third largest proven reserves (and will likely move up the list of oil-rich nations to become the second largest once additional exploration is completed). Despite its sizeable reserves, Iraq has not sustained rates above 3 mbbd for any significant period of time since the 1979 Iran-Iraq War. In addition, the majority of Iraq's 4,300-mile pipeline system has suffered from poor maintenance and the effects of a ten-year embargo, looting and war.

Despite sizeable commitments of troops and resources, the overall condition of the Iraqi oil network has not significantly improved since the overthrow of Saddam Hussein. Frequent attacks against Iraq's key infrastructure continue to cost the Iraqi government and the United States millions of dollars each week. Since the beginning of Operation Iraqi Freedom, Iraq has sustained over $7 billion in damages [Barazanji, 2004, et. al. Some sources estimate the damages as high as $12 billion U.S. dollars] to its oil infrastructure as a result of 257 attacks (the most recent occurring August 4, 2005,

following a series of three explosions resulting in damage to the pipeline between Kirkuk and Bayji) [IAGS, 2005]. These types of attacks are particularly troublesome because without efficient and reliable oil production – Iraq's principal resource – the newly-established government cannot generate the funds needed to repair damaged infrastructure. It also cannot attract outside capital to fund long-term improvements to the pipeline network or modernize its refineries to support domestic fuel requirements. Unfortunately, all of these difficulties are occurring at the same time that world oil markets are near an all-time high price per barrel of crude. For this reason, we examine the network that transports Iraq's most valuable resource and assess those segments of the pipeline in most need of repair, protection, or additional upgrades and redundancies.

1. Problem Statement and Relevance to Stability and Support Operations

We investigate the advantages and difficulties of developing an optimal interdiction and capital expansion model of the Iraqi crude oil distribution network. The concept of protecting this infrastructure is not new, nor is the threat. In present-day Iraq U.S. forces and Iraqi nationals are engaged daily in an ongoing struggle against an enemy whose tactics are comparable to those of other guerrilla forces around the world. While it is not widely discussed by the mainstream media, attacks on oil infrastructure are a regular occurrence around the world, and the United States has involved itself when necessary to aid in protecting it. In regions such as Georgia, Azerbaijan, and other parts of Eastern Europe, the United States has provided substantial military assistance for training and equipping military forces assigned to protect oil infrastructure [Klare, 2004]. The same is true in countries closer to home such as embattled Columbia. Since 2002, U.S. forces have assumed increasing responsibility for protection of that country's vulnerable oil pipelines and hundreds of millions of dollars have been appropriated to enhance oil infrastructure security, beginning with the Cano-Limon pipeline [Klare, 2004, Dauenhauer, 2003, et al.]. Even in the United States, the Alaska pipeline has been the target of at least fifty random attacks and at least one failed terrorist threat [Clark, 2001]. So the importance of improving infrastructure defense - in general - has been a

topic of importance for some time and has enjoyed renewed interest since September 11th.

2. Existing Iraqi Oil Distribution Network and Candidate Expansion Opportunities

Iraq's network of pipelines for transporting crude oil spans somewhere between 3,300 and 4,300 miles [Greste, 2004 and Luft, 2004] depending on whether you include abandoned pipelines. In addition, there are another 830 miles used for transporting refined fuels and 1,081 miles of natural gas pipelines. We focus exclusively on the crude oil distribution system. Figure 1 illustrates all of the major crude oil pipelines, as well as several potential pipeline expansion projects.

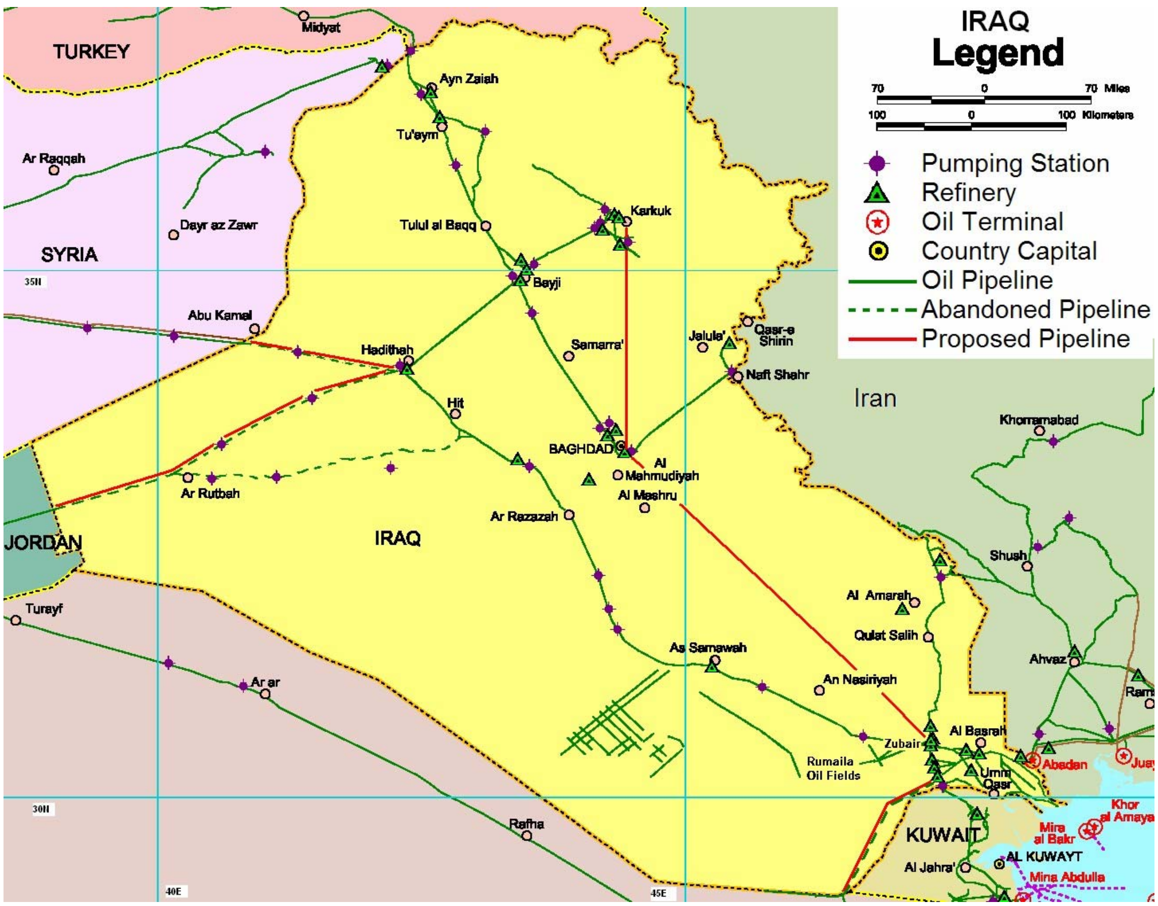


Figure 1. Map of Iraq's Existing and Proposed Crude Oil Infrastructure

At present the country's oil sector is divided into two basic regions with Iraq's Northern Oil Company (NOC) overseeing northern and central Iraq, and Iraq's Southern Oil Company (SOC) overseeing southern Iraq and the two large off-shore loading facilities at Basra (formerly Mina al-Bakr) and Khor al-Amaya in the Persian Gulf. Because of the steady frequency of attacks against the northern oil route (oil flowing from Kirkuk and East Baghdad to Turkey's Ceyhan port in the Meditarranean) exports to Turkey have been sporadic since 2003. The majority of Iraq's oil production is presently extracted from the giant southern Rumeila and Zubair oil fields and reservoir. Like everywhere else in Iraq these areas are experiencing steady declines in production. As recently as May of this year Iraq was exporting between 1.4 and 1.5 mbbd from the Basra and Khor al-Amaya terminals [Alexander, 2005c]. Based on their published capacities Basra has a maximum capability to load nearly 2.0 mbbd and Khor al-Amaya approximately 1.6 mbbd.

Export routes to several of Iraq's neighbors did at one time exist. Syria and Iraq were connected by a 650 kbbd pipeline from Iraq's northern Kirkuk oil fields to Syria's Mediterranean port of Banias up until 1982. It was at that time that Syria blocked flows on the pipeline as a show of support for Iran during the Iran-Iraq War. In July 1998 – post Desert Storm – Iraq and Syria entered into negotiations to reopen the line but did not secure U.N. approval for such a measure. Oil is believed to have moved unofficially via this channel on a number of occasions following these negotiations in direct violation of the UN's Oil for Food program. Then in March 1993 the pipeline was officially closed again by coalition forces seeking to stem the flow of illegal oil leaving the country. In March 2004, this same pipeline was again reported available for more modest flows of approximately 250 kbbd [Feld, 2005b].

In September 1987, construction of a $1.5 billion spur line from Zubair in southern Iraq to Saudi Arabia was completed. This 1.65 mbbd high-capacity line was originally constructed as an alternate export channel for Iraqi oil during the Iran-Iraq war. When completed it allowed oil to move from southern Iraq across Saudi Arabia to the Red Sea port of Mu'ajiz, just north of Yanbu. This pipeline, however, only operated for two years before it was closed by Saudi Arabia following Iraq's invasion of Kuwait in

August 1990. Since that time Saudi Arabia has expropriated those sections of the pipeline within its borders and converted it to a natural gas pipeline. The Iraqi sections of the pipeline in turn have been looted extensively and are described as not being in a usable form because of its long-term closure [Aljazeera, 2003].

Construction of a pipeline connecting Iraq's northern oil fields and Jordan's al-Zarqa refinery has been a topic of discussion for over two decades. In 1985 plans were underway to build a 1.5 mbbd pipeline following the right-of-way lines established by the old Iraq Petroleum Company (IPC) from Kirkuk to a point north of Amman, then proceeding south to al-Agabah [Gates, 1985]. This project was never initiated for lack of funding and the ongoing Iran-Iraq war. Then in 2001, numerous reports again appeared indicating that the Jordanian government was close to completing a $350 million (U.S.) agreement to replace its nearly 90 kbbd oil tanker-truck fleet with a new pipeline capable of transporting as much as 350 kbbd [Dalal, 2004, et. al.]. At present, this project resides only on paper within Iraq's borders though some work is believed to have been accomplished in Jordan.

Iraq and Kuwait share a 124-mile border. In July 1990, Iraq accused Kuwait of "attempting to weaken Iraq", encroaching on Iraqi territory, draining oil from the Rumaila field which straddles the border between these two countries, and colluding with the United Arab Emirates to "flood the oil market…and collapse oil prices." [Feld, 2005b]. Shortly afterwards, Iraq moved as many as 30,000 troops to the Iraqi-Kuwaiti border and set in motion a chain of events leading up to the first Gulf War. Kuwait and Iraq have maintained cool relations ever since. However, recent diplomatic exchanges between the two countries following the ousting of Saddam Hussein have suggested that limited "swap" arrangements and export opportunities may exist between them in the future.

Similar arrangements are virtually certain to be approved between Iran and Iraq. The most likely of these proposals is an oil exchange agreement of approximately 250 kbbd (and potentially more) in which Iraq will pump crude oil to Iran's Abadan refinery on Kharg Island and would receive in return an equal amount of refined products that are

desperately needed to meet critical shortages in gasoline, kerosene and diesel fuel [Mehr, 2005, et. al.].

Iraq's largest pipeline is the 600-mile dual-channel Kirkuk-Ceyhan (Turkey) pipeline. It has a published capacity of 1.6 mbbd but reportedly could only handle around 900 kbbd before Operation Iraqi Freedom [Feld, 2005a]. Prior to the war over 40% of Iraq's oil exports were transported via this route [Giragosian, 2004], however, since liberation this stretch of pipeline has been the target of repeated attacks and is only operational sporadically, thereby necessitating the almost exclusive use of the southern export channels. We assume that extensive repairs are required to achieve any sustained capacity above fifty percent.

Lastly, there is the renovation of Iraq's 1.4 mbbd "Strategic North-South Oil Pipeline." Completed in 1975, this pipeline was originally constructed to optimize export capabilities by facilitating both north and south movement of oil to match export capacity with demand. The pipeline consists of two parallel 700 kbbd lines. During the first gulf War this pipeline was disabled after the K-3 pump station at Haditha, as well as four other pump stations were destroyed. Today, the exact status of this pipeline is not precisely known. We optimistically assign it a capacity of 700 kbbd from Pump Station K-3 (Haditha) to Zubair. We also consider a second – previously unconstructed – north-south pipeline connecting Kirkuk with East Baghdad then continuing south to Zubair. The length of this pipeline would be about 470 miles, and we assume the engineering details are comparable to other previous new construction projects. Offering an option for such an ambitious addition to the Iraqi network explores the effects and improvements that might be achievable through expanded capacity and redundancy in the oil distribution network.

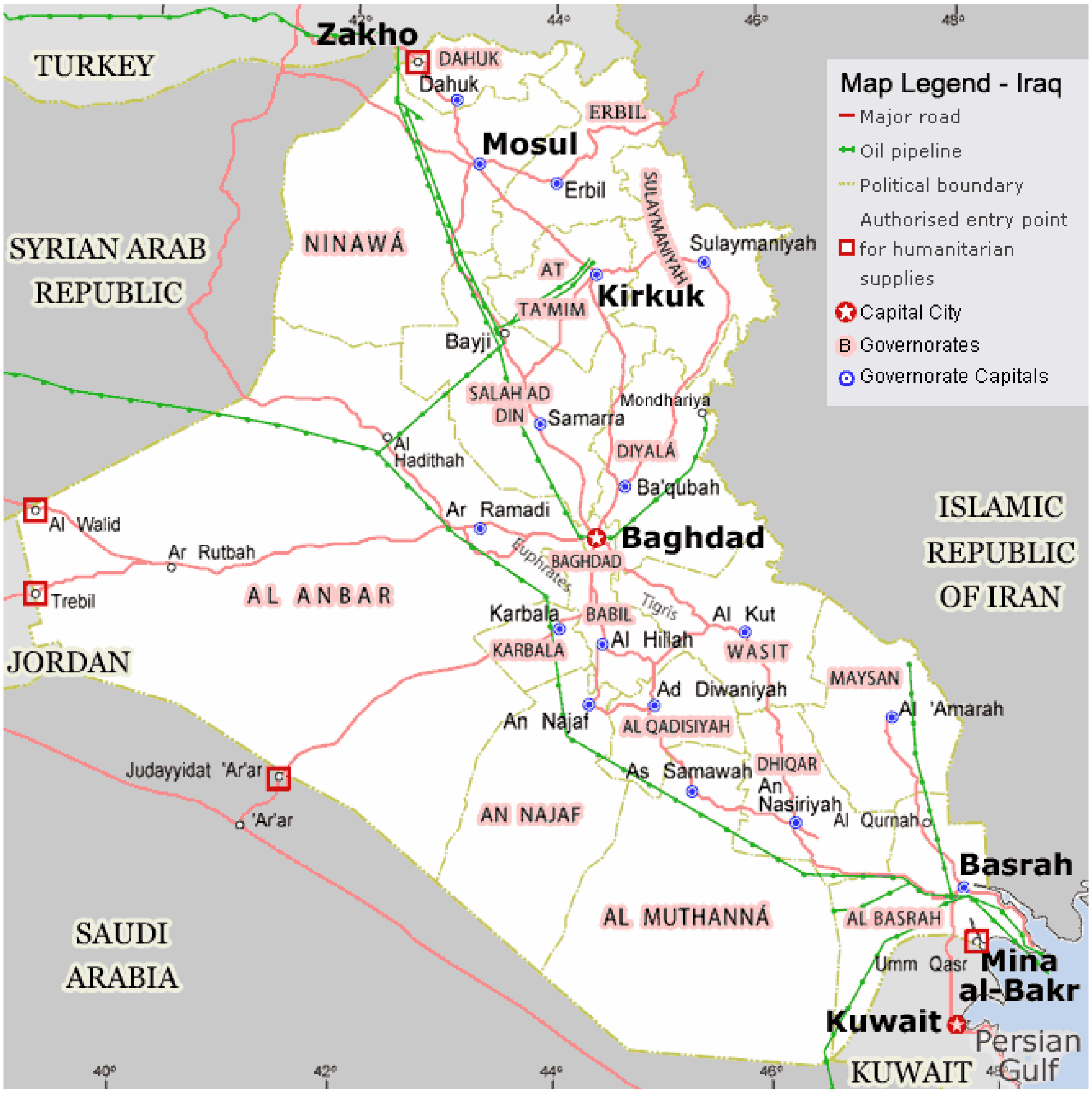


Figure 2. Map of Iraq's Major Road and Oil Export Network [IAGS, 2005]

3. Insights to be Gained from this Research

We seek insights for the following questions:

(1) What are the optimal interdiction points on the current and future Iraqi oil distribution network that an insurgent might target if he wishes to minimize the amount of export flow from the network?

(2) Given a finite amount of dollars to expand and defend oil infrastructure, what additional pipeline sections produce the greatest improvement in flow capacity and contribute to a more robust network over the next ten years?

We represent Iraq's oil infrastructure based on open-source documentation and unclassified government reports of Iraq's crude oil pipelines. Our first goal is to assess the criticality of specific pipelines and transfer points in the current configuration that when lost are likely to drive overall crude oil distribution below 3 mbbd. The coalition and Iraqi government have announced a goal for a sustained crude oil production rate between 2.8 and 3.0 mbbd, an achievable benchmark based on the maximum average flow sustained by Iraq prior to its war with Iran in 1979.

Attaining an objective flow rate is important but not sustainable if we cannot also build a robust distribution network. Our second goal is to study the effectiveness of specific infrastructure expansion and defense measures attainable by allocating a fixed budget over a multi-year planning horizon. Numerous post-war Iraq surveys estimate the capital required to rehabilitate the oil industry ranges from 2 to 45 billion dollars over the next 10 years. Much of Iraq's capital expansion traditionally comes from private industry; however, the ongoing looting and destruction of the infrastructure, intimidation and violence against technical personnel, as well as uncertain political and legal considerations that can only be resolved by an elected government, are likely to deter private investment in the short term. For this reason, a sizeable initial investment is likely required to implement any portion of this proposal until security can be restored. In 2003, the U.S. Congress approved $18.4 billion in aid for Iraq. Only a portion of this amount was ever earmarked for the oil industry, and to date very little of that has been spent on improving actual infrastructure [Feld, 2005a]. Theoretically, if remaining funds are used or new sources appropriated, a reasonable starting figure supported by a number of sources for achieving pre-war oil production levels is about $6 billion. This is why answering the second question is so important. Because the price tag for improving and repairing the infrastructure is relatively large, it is critical to determine which projects most improve the overall flow rate and survivability of the distribution system. More importantly, can we quantify what the return on investment is in terms of additional oil available for export if we add redundant capacity and defend the infrastructure better?

THIS PAGE INTENTIONALLY LEFT BLANK

II. MODEL DEVELOPMENT

If you build it they will come – and then they'll try to blow it up

LtCol Lee Morrison,
U.S. Army Corps of Engineers

A. OVERVIEW

We seek a multi-year capacity expansion investment plan for Iraq's crude oil delivery system that allocates funds between capacity expansion activities and defense of completed infrastructure. Our goal is to maximize the quarterly volume of crude oil delivered out of Iraq for sale.

These construction projects are so large and costly that we cannot expect to hide our plans. We anticipate that insurgents will have full prior knowledge of our construction and defense plans, and will carry out their attacks to the best of their ability on our vulnerable infrastructure to minimize our capacity to pump crude oil out of Iraq.

As a preliminary, expository step, we present a maximum-flow model of an existing oil delivery system, and show how to optimize insurgent attacks to minimize this maximum flow. There is no defense here, and the vulnerability of existing infrastructure is an exogenous constant, known to both adversaries.

We then generalize to a multi-period (e.g., quarterly, for ten years) capacity expansion investment model, and embellish this with defensive options that decrease vulnerability and/or recovery time from insurgent attacks. The defensive options consume funds that would otherwise be devoted to construction. We still want to maximize deliveries out of Iraq, and the insurgents want to minimize these.

B. DEVELOPING THE CAPITAL EXPANSION AND INTERDICTION MODEL

1. Optimizing Maximum Flow through a Capacitated Network, Subject to Interdictions: A Bi-level Attacker-Defender Model with Defender Represented by a Linear Program

We want to move crude oil through a capacitated flow network consisting of a directed graph *G=(N,A)*, where *N* is a set of nodes, and *A* is a set of directed arcs connecting node pairs, and each arc has a maximum flow capacity. Our opponent's objective is to minimize our maximum flow through this network from some distinguished source node *s* to some other distinguished terminal node *t*.

We employ an activity-on-arc model: the analogy between a length of oil pipe and an arc is obvious. We must also represent oil-handling facilities such as tank farms and pumping stations, *and these are also represented as arcs*. For instance, a pumping facility is represented by an entry and exit node connected by a capacitated arc representing the volume of crude pumped per day.

The attacker has the capability to destroy a limited number of arcs, reducing each destroyed arc capacity to zero for some number of days, and must decide which arcs in the network to destroy so that our maximum flow is minimized – perhaps to zero – until the damage can be repaired.

A basic maximum flow model with arc interdictions follows.

Index Use

$n \in N$	node (alias *i*, *j*)
s, *t*	source, terminal nodes
$(i, j) \in A$	arc directed from node *i* to node *j*
$(i, j) \in R \equiv A \setminus (t, s)$	arcs, excluding back-arc (*t*,*s*) directed from node *i* to node *j*

Data [units]

$u_{i,j}$	upper bound on flow from node *i* to node *j* [flow]
$v_{i,j}$	penalty cost [fraction of flow interdicted]
$\overline{attacks}$	maximum number of arcs the attacker can destroy [cardinality]

Decision Variables [units]

$FLOW_{i,j}$ operator flow on directed arc $(i,j) \in A$ [flow]

$ATTACK_{i,j}$ 1 if attacker attacks arc $(i,j) \in R$, 0 otherwise [binary]

Minimax optimization of flow [dual variables]

$$\min_{ATTACK \in \Upsilon} \left\{ \begin{array}{llll} \max\limits_{FLOW} & FLOW_{t,s} - \sum\limits_{(i,j)\in R} v_{i,j} ATTACK_{i,j} FLOW_{i,j} & & \\ s.t. & \sum\limits_{(i,n)\in A} FLOW_{i,n} - \sum\limits_{(n,j)\in A} FLOW_{n,j} = 0 & \forall n \in N & [\alpha_n] \\ & 0 \le FLOW_{i,j} \le u_{i,j} & \forall (i,j) \in R & [\beta_{i,j}] \end{array} \right\}$$

$$\text{where } ATTACK \in \Upsilon = \left\{ \begin{array}{ll} \sum\limits_{(i,j)\in R} ATTACK_{i,j} \le \overline{attacks} & \\ ATTACK_{i,j} \in \{0,1\} & \forall (i,j) \in R \end{array} \right\}$$

Node s is connected by invulnerable arcs (that do not represent physical entities and are merely a modeling device) to each source node in Iraq, and invulnerable arcs connect each exit node from Iraq to node t. The back-flow on arc (t,s) in the objective function represents the amount of oil pumped out of Iraq to market. The second term in the objective penalizes planned flows by the diminished capacities of attacked arcs.

For complete interdiction of flow on arc (i,j), the (finite) penalty cost $v_{i,j}$ can be chosen to be any number greater than 1. If $v_{i,j} = 1$, then we are completely indifferent about sending flow over the interdicted arc, and the resulting problem may therefore have many equivalent optimal solutions. For any value $v_{i,j} > 1$, we will be penalized for that flow, and therefore will not send any flow across the interdicted arc.

We envision a model with quarterly time resolution. Over the span of a quarter, damage from any attack can be repaired, though some arcs (e.g., pipelines) are easier to repair than others (e.g., pump stations). For such an attacked arc (i,j), $v_{i,j} < 1$ represents the fraction of planned flow lost during a repair epoch.

If we wish to make an arc invulnerable to attack, we just set $v_{i,j} = 0$. Then interdiction of that arc has no effect on the flow across the arc, and would be wasted effort.

Observing that the inner, maximization problem is a linear program, if we hold *ATTACK* constant momentarily, we can solve this linear program by minimizing the duals. The result is the following mixed-integer program:

Mixed integer linear program minimizing maximum flow

$$
\begin{array}{lll}
\min\limits_{\substack{\alpha,\beta,\\ ATTACK}} & \sum\limits_{(i,j)\in R} u_{i,j}\beta_{i,j} & \\
s.t. & \alpha_i - \alpha_j + \beta_{i,j} + v_{i,j} ATTACK_{i,j} \geq 0 & \forall (i,j)\in R \\
& \alpha_t - \alpha_s + \beta_{t,s} \geq 1 & \\
& \sum\limits_{(i,j)\in R} ATTACK_{i,j} \leq attacks & \\
& \alpha_s = 0 & \\
& \alpha_n \quad \text{unrestricted in sign} & \forall \mathrm{n} \in \mathrm{N} \\
& \beta_{i,j} \geq 0 & \forall (i,j)\in R \\
& ATTACK_{i,j} \in \{0,1\} & \forall (i,j)\in R
\end{array}
$$

Using a feasible binary attack plan $ATTACK^*$ from this mixed integer linear program (LP), we can recover our residual flows $FLOW^*$ by solving our seminal maximizing linear program for this fixed $ATTACK^*$. (The values of the dual variables might not allow a direct calculation of the optimal flow; they can, in fact, be non-integer, even though we would expect them to label the nodes and arcs of the minimum interdicted cut just as they would in the standard min-cut formulation [Wood, 1993].

The mixed integer linear program can be embellished by any LP restrictions on the *ATTACK* variables.

2. A Bi-Level Defender-Attacker Model, with Defender Choosing Capacity Expansion and Defense options, and Maximizing Flows, and Attacker Interdicting the Results: Each Opponent is Represented by an Integer Linear Program.

We now want to generalize to a multi-period flow capacity expansion model, where our construction budget is limited, and our defensive options consume funds that

would otherwise be devoted to construction. We still want to maximize deliveries out of Iraq, and the insurgents want to minimize these. Unlike the simple illustrative example above, the capacity expansion model needs to feature binary decisions, and is an integer linear program, and the attacker model features general integer decisions. Accordingly, we cannot employ duality to render a conventional model to solve. Instead, we develop a new, two-sided decomposition.

We restate our notation to accommodate a planning horizon.

Model FLOW

Index Use [~ cardinality]

$q \in Q$	planning quarter (alias *q'*) [~40]
$d \in D$	duration in quarters (alias *d'*) [<<40]
$n \in N$	node (alias *i*, *j*) [~100]
s, *t*	source, terminal nodes
$(i, j) \in A$	directed arcs [~200]
$(i, j) \in R \equiv A \setminus (t, s)$	arcs, excluding back-arc (*t*,*s*) directed from node *i* to node *j*
$(i, j) \in P \subseteq R$	arc candidate for capacity expansion project [~200]
$\{i, j, q, d\}$	4-tuple identifying an admissible project on arc $(i, j) \in P$ [~4,000?]
$c \in C$	iteration (or "cut") counter [~100?]

Data [units]

$u_{i,j}$	legacy upper bound on flow from node *i* to node *j* [flow]
$x_{i,j}$	expanded capacity from node *i* to node *j* [flow]
$build\_cost_{i,j.d,d'}$	if capacity expansion of arc $(i, j) \in P$ has scheduled duration *d* quarters, this cost is incurred in quarter *d'* of the construction effort ($1 \le d' \le d$) [cost]
$defense\_cost_{i,j}$	cost of defending arc $(i, j) \in R$ [cost/flow]
BUDGET	total capacity expansion budget [cost]
$budget_q$	capacity expansion budget goal for quarter *q*, $\sum_{q \in Q} budget_q = BUDGET$ [cost]
$\underline{spendpen}, \overline{spendpen}$	penalty per unit of cumulative under, or over expenditure [flow/cost]
$v_{i,j}$	penalty cost ($0 \le v_{i,j} \le 1$) [if attacked, fraction of flow interdicted]
$d_{i,j}$	defense effectiveness ($0 \le d_{i,j} \le v_{i,j}$) [fraction of flow defended]
epoch_q	epoch in quarters for limiting attacks [quarters]

epoch_attacks maximum attacks allowed in epoch [cardinality]
atks_by_q maximum attacks by quarter [cardinality]
mx_atks maximum attacks over planning horizon [cardinality]
atks_by_n_by_q maximum attacks of arcs incident to each node, by quarter [cardinality]
$\overline{attacks}_{i,j,q}$ maximum attacks of each arc, by quarter [cardinality]

Decision Variables [units]
$START_{i,j,q,d}$ =1 if capacity expansion project $\{i, j, p, d\}$ is selected, 0 otherwise [binary]
$DEFEND_{i,j,q}$ =1 if arc $(i, j) \in R$ is defended during planning quarter *q*, 0 otherwise [binary]
$FLOW_{i,j,q}$ flow on directed arc $(i, j) \in A$ during planning quarter *q* [flow]
$SAVE_{i,j,q}$ lost flow prevented by defense of arc $(i, j) \in R$ [flow]
$\underline{SPEND}_q, \overline{SPEND}_q$ under-, over-expenditure of cumulative quarterly budget goals through planning quarter *q* [cost]
$ATTACKS_{i,j,q}$ number of attacks on arc $(i, j) \in R$ during planning quarter *q*., [integer]

These decision variables appear in lowercase when their values are temporarily fixed, and UPPERCASE otherwise.

$$\max_{\substack{START,DEFEND,\\ FLOW,\underline{SAVE},\\ \underline{SPEND},\overline{SPEND}}} \sum_{q\in Q} FLOW_{t,s,q} - \sum_{(i,j)\in R, q\in Q} \left(v_{i,j} attacks_{i,j,q} FLOW_{i,j,q} - d_{i,j} attacks_{i,j,q} SAVE_{i,j,q} \right)$$

$$-\sum_{q\in Q} \underline{spendpen}\, \underline{SPEND}_q - \sum_{q\in Q} \overline{spendpen}\, \overline{SPEND}_q \qquad \text{(F0)}$$

$$s.t. \qquad \sum_{(i,n)\in A} FLOW_{i,n,q} - \sum_{(n,j)\in A} FLOW_{n,j,q} = 0 \qquad \forall n\in N, q\in Q \qquad \text{(F1)}$$

$$FLOW_{i,j,q} \le u_{i,j} + \left[x_{i,j} \sum_{\substack{q'\in\{i,j,q',d\},\\ q'+d-1\le q}} START_{i,j,q',d} \right]_{(i,j)\in P} \qquad \forall (i,j)\in R, q\in Q \qquad \text{(F2)}$$

$$SAVE_{i,j,q} \le FLOW_{i,j,q} \qquad \forall (i,j)\in R, q\in Q \qquad \text{(F3)}$$

$$SAVE_{i,j,q} \le (u_{i,j} + \left[x_{i,j} \right]_{(i,j)\in P}) DEFEND_{i,j,q} \qquad \forall (i,j)\in R, q\in Q \qquad \text{(F4)}$$

$$\sum_{\substack{(i,j)\in P,\\ q',d\in\{i,j,q',d\},\\ q'\le q}} \left(\sum_{d'\le \min(d,q-q'+1)} build\_cost_{i,j,d,d'} \right) START_{i,j,q',d}$$

$$+ \sum_{(i,j)\in R, q'\le q} defense\_cost_{i,j}\, DEFEND_{i,j,q'}$$

$$+\underline{SPEND}_q - \overline{SPEND}_q = \sum_{q'\le q} budget_{q'} \qquad \forall q\in Q \qquad \text{(F5)}$$

$$\sum_{\substack{q\in Q,\\ d\in\{i,j,q,d\}}} START_{i,j,q,d} \le 1 \qquad \forall (i,j)\in P \qquad \text{(F6)}$$

$$START_{i,j,q,d} \in \{0,1\} \qquad \forall i,j,q,d \in \{i,j,q,d\} \qquad \text{(F7)}$$

$$DEFEND_{i,j.q} \in \{0,1\} \qquad \forall (i,j)\in R, q\in Q \qquad \text{(F8)}$$

$$FLOW_{i,j,q} \ge 0 \qquad \forall (i,j)\in A, q\in Q \qquad \text{(F9)}$$

$$SAVE_{i,j,q} \ge 0 \qquad \forall (i,j)\in R, q\in Q \qquad \text{(F10)}$$

$$\underline{SPEND}_q, \overline{SPEND}_q \ge 0 \qquad \forall q\in Q \qquad \text{(F11)}$$

The objective (F0) expresses how much oil is exported out of Iraq over the planning horizon. Each attack on an arc reduces flow by an amount that reflects the time necessary to repair damage, while an attack on a defended arc will inflict less damage, or perhaps no damage at all, depending on the effectiveness of the defense effort. There are also penalties for under- or over-spending the cumulative budget through the end of each quarter in the planning horizon. Each of these objective terms is in units of exported oil.

For instance, an over-spending violation (e.g., in dollars over-spent) is converted by penalty (e.g., in oil per dollars over-spent) and converted into exported oil units.

Each constraint (F1) enforces conservation of flow into and out of each node. Each constraint (F2) limits the flow on an arc by its legacy capacity, or, for an arc candidate selected for capacity expansion, by the sum of its legacy capacity and the expanded capacity starting in the quarter after arc expansion is completed. Each constraint (F3) limits the effects of a defense effort on an arc to the amount of oil actually lost when the arc is attacked. Each constraint (F4) limits the effects of a defense effort on an arc to zero unless that defense is mounted. Each constraint (F5) assesses the total spending through the end of a planning quarter, and determines whether there is any under- or over-spending with respect to the cumulative budget target at the end of that quarter. Each constraint (F6) assures that at most one capacity expansion option is adopted for a candidate arc. Stipulations (F7-F11) are domain limits on decision variables.

A more direct way of expressing the objective is:

$$\max_{\substack{START, DEFEND,\\ FLOW, \underline{SAVE},\\ \underline{SPEND}, \overline{SPEND}}} \sum_{q \in Q} FLOW_{t,s,q} - \sum_{(i,j) \in R, q \in Q} \left([v_{i,j} - d_{i,j} DEFEND_{i,j,q}] \, attacks_{i,j,q} FLOW_{i,j,q} \right)$$

$$- \sum_{q \in Q} \underline{spendpen} \, \underline{SPEND}_q - \sum_{q \in Q} \overline{spendpen} \, \overline{SPEND}_q \qquad \text{(F00)}$$

However, this is not linear in ***DEFEND*** and ***FLOW***. The auxiliary variables *SAVE*, objective (F0), and constraints (F3) and (F4) are equivalent, and linear.

Given a plan to expand capacity, operate, and defend the Iraqi oil export system through the end of the planning horizon, an attacker with perfect knowledge of this plan would counter-plan accordingly:

Model ATTACK:

$$\min_{ATTACKS} \sum_{q\in Q} flow_{t,s,q} \quad - \sum_{(i,j)\in R, q\in Q} \left([v_{i,j} - d_{i,j} defend_{i,j,q}] ATTACKS_{i,j,q}\, flow_{i,j,q} \right)$$
$$- \sum_{q\in Q} \underline{spendpen}\,\underline{spend}_q - \sum_{q\in Q} \overline{spendpen}\,\overline{spend}_q \qquad \text{(A0)}$$

$$s.t. \quad \sum_{q \le q' \le = q+epoch\_q-1} ATTACKS_{i,j,q} \le epoch\_attacks \qquad \forall (i,j)\in R, \forall q\in Q,$$
$$q \le |Q| - epoch\_q - 1 \quad \text{(A1)}$$

$$\sum_{(i,j)\in R} ATTACKS_{i,j,q} \le atks\_by\_q \qquad \forall q \in Q \qquad \text{(A2)}$$

$$\sum_{(i,j)\in R, q\in Q} ATTACKS_{i,j,q} \le max\_atks \qquad \text{(A3)}$$

$$\sum_{(i,j)\in R} ATTACKS_{i,n,q} + \sum_{(i,j)\in R} ATTACKS_{n,j,q} \le atks\_by\_n\_by\_q \qquad \forall n\in N, q\in Q \qquad \text{(A4)}$$

$$\sum_{\substack{(i,j)\in R, q\in Q, \\ | attack^c_{i,j,q}=0}} ATTACKS_{i,j,q} \ge 1 \qquad \forall c\in C \qquad \text{(A5)}$$

$$ATTACKS_{i,j,q} \in \{0,1,...\overline{attacks}_{i,j,q}\} \qquad \forall (i,j)\in R, q\in Q \qquad \text{(A6)}$$

The attacker's objective (A0) is to minimize net oil exports over the planning horizon, precisely the opposite of the Iraqi operator's objective (F0). Each attack inflicts damage determined by the vulnerability of the arc attacked (expressed in terms of the fraction of planned quarterly oil flow reduced during repairs), mitigated by any defense effort in place. Some arcs may be invulnerable to attack with no defense at all, and others may be able to be defended well enough to render them invulnerable.

The constraints (A1)-(A4) offer some examples of how to moderate attacker behavior: Given that this is an integer-linear program, you are limited only by your imagination. Each constraint (A1) optionally limits the number of quarters between attacks on any given arc. Each constraint (A2) optionally limits the total number of attacks by quarter. Constraint (A3) optionally limits the total number of attacks over the planning horizon. Each constraint (A4) optionally limits the number of attacks on arcs

adjacent to each node in a given quarter. (A6) specifies the integer domain of each attack variable. In practice:

$$\overline{attacks}_{i,j,q} = \begin{cases} \left\lfloor 1/v_{i,j} \right\rfloor, \text{if } v_{i,j} > 0 \\ 0 \qquad , \text{otherwise} \end{cases} \qquad , \forall (i,j) \in R, q \in Q;$$

That is, attack effectiveness is limited to interdict no more than 100% of the oil at risk.

We are going to solve a sequence of (***ATTACK***) models, and each constraint (A5) stipulates that the current planned revision of (***ATTACK***) differs in at least one detail from each legacy attack plan: at least one arc must be attacked that has never before been attacked.

For binary *ATTACKS*, a single constraint can be used to force some distinguishing difference from each legacy attack plan [Brown, et. al., 1997]:

$$\sum_{\substack{(i,j)\in R, q\in Q \\ |attacks^{c}_{i,j,q}=0}} ATTACKS_{i,j,q} + \sum_{\substack{(i,j)\in R, q\in Q \\ |attacks^{c}_{i,j,q}=1}} (1 - ATTACKS_{i,j,q}) \geq 1, \; c \in C \qquad \text{(B5)}$$

For integer ATTACKS, a set of constraints is required. Let $B^{+}_{i,j,q}, B^{-}_{i,j,q}$ be binary variables, and formulate:

$$\begin{aligned} &ATTACKS_{i,j,q} \geq attacks^{c}_{i,j,q} + B^{+}_{i.j,q} \qquad \forall (i,j) \in R, q \in Q, c \in C \mid attacks^{c}_{i,j,q} < \overline{attacks}_{i,j,q} \\ &ATTACKS_{i,j,q} \leq attacks^{c}_{i,j,q} - B^{-}_{i.j,q} \qquad \forall (i,j) \in R, q \in Q, c \in C \mid attacks^{c}_{i,j,q} > 0 \\ &\sum_{\substack{(i,j)\in R, q\in Q, \\ |0<attacks^{c}_{i,j,q}<\overline{attacks}_{i,j,q}}} (B^{+}_{i,j,q} + B^{-}_{i.,j,q}) \geq 1 \qquad \forall c \in C \end{aligned} \qquad \text{(I5)}$$

For our purposes, the restricted constraints (A5) suffice, although they rule out revisions that are admissible in (I5).

The bi-level, defender-attacker optimization proceeds as follows.

0) Initialize the current attack plan to have no attacks. Set iteration $c = 0$.
1) Given the current attack plan, solve the defender mixed integer program (***FLOW***), yielding a complete capital expansion, oil export, and defense plan for the planning horizon.
2) This defender plan assumes perfect knowledge of a fixed current attack plan, and is thus optimistic. Under certain conditions, the value of (F0) may provide an upper bound on the highest net oil export achievable.
3) Given the defender plan, the attacker uses the mixed integer program (***ATTACK***) to minimize the observed planned flows with a set of attacks that differs in at least one detail from each of the *c* prior, legacy attack plans.
4) The revised attack plan provides a candidate plan that may be the lowest net oil export achieved. Increase $c = c + 1$, and record the revised, current attack plan as the *c*-th legacy plan.
5) Repeat Steps 1) to 4) until the gap between the highest and lowest net oil export is sufficiently small, or until reaching some iteration limit.
6) Recover the best legacy (***FLOW***) and (***ATTACK***) plan discovered.

The first solution of (***FLOW***) in Step 2) assumes no attacks at all. As such, this is a best-case solution for Iraq, and the net oil export is an upper bound on what is achievable with or without insurgent attacks.

The first solution of (***ATTACK***) in Step 3) attacks a solution to (***FLOW***) that anticipates no attack at all. This is a "surprise attack" that gives us a lower bound on the net oil export achievable. Each subsequent solution in Step 3) may provide the highest lower bound on net oil export achievable. The highest such lower bound is the best two-sided plan, where the defender must lead with a complete plan, and then the attacker can observe (or gather intelligence about) this plan and follow by attacking it optimally.

In subsequent iterations, each Step 2) solution of (***FLOW***) may give us a better upper bound. For the value of the objective (F0) to be a candidate for upper bound

improvement, the fixed attack plan must have no taut constraint in (A5). That is, if the fixed attack plan found by minimizing (A0) is intrinsically distinct from each prior attack plan, then this optimization of (***ATTACK***) minimizes the same objective that (***FLOW***) maximizes, and thus the value of (***ATTACK***) may be a better upper bound.

The (***ATTACK***) objective assumes that all flows are fixed. This is optimistic for the attacker. However, when the subsequent (***FLOW***) model is solved given this attack, the response will optimally circumvent the latest attacks.

3. A Tri-Level Defender-Attacker-Defender Model, with Defender Choosing Capacity Expansion and Defense options, Attacker Interdicting the Results, and Defender Responding to Interdictions by Maximizing Flow Using the Remaining Capacity in the Damaged System.

Suppose, more realistically, that the defender determines an optimal capacity expansion and defense plan with a set of maximal flows. If we fix these capacity expansion and defense decisions, but allow the operator to maximize residual flows after any attack, we have a tri-level defender-attacker-defender model [Brown, et. al., 2005b]:

$$\max_{\mathbf{z} \in Z} \min_{\mathbf{x} \in X(\mathbf{z})} \max_{\mathbf{y} \in Y(\mathbf{x})} \mathbf{cy}.$$

Here, z denotes a vector of binary capacity expansion and defense decisions, as well as spending penalty variables, $z \in Z$ represents the constraints and domain restrictions on these decisions, and the inner min-max problem represents an attacker-defender model with a restricted set of attack strategies $X(z)$. $y \in Y(x)$ represents the defender's residual capability to manipulate flows after the attacks, and cy is the objective function expressing net oil flow export. The defender wants to identify a capital expansion and defense plan z^* so that when the attacker solves:

$$\min_{\mathbf{x} \in X(\mathbf{z}^*)} \max_{\mathbf{y} \in Y(\mathbf{x})} \mathbf{cy}.$$

The flow reduction the attacker can guarantee to inflict is minimized by the operator's responses.

We do not know of any direct means to formally solve tri-level defender-attacker-defender models. We propose the following (indirect) decomposition. Restate (***FLOW***) with binary decisions *START*, *DEFEND*, spending violations, and integer *ATTACKS* fixed:

Model DIVERT_FLOW

$$\max_{FLOW,SAVE} \sum_{q\in Q} FLOW_{t,s,q} - \sum_{(i,j)\in R, q\in Q} \left(v_{i,j} attacks_{i,j,q} FLOW_{i,j,q} - d_{i,j} attacks_{i,j,q} SAVE_{i,j,q} \right)$$
$$- \sum_{q\in Q} \underline{spendpen}\, \underline{spend}_q - \sum_{q\in Q} \overline{spendpen}\, \overline{spend}_q \qquad \text{(DF0)}$$

$$s.t. \quad \sum_{(i,n)\in A} FLOW_{i,n,q} - \sum_{(n,j)\in A} FLOW_{n,j,q} = 0 \qquad \forall n \in N, q \in Q \qquad \text{(DF1) } [\alpha]$$

$$FLOW_{i,j,q} \le u_{i,j} + \left[x_{i,j} \sum_{\substack{q' \in \{i,j,q',d\}, \\ q'+d-1 \le q}} start_{i,j,q',d} \right]_{(i,j)\in P} \qquad \forall (i,j) \in R, q \in Q \qquad \text{(DF2) } [\beta]$$

$$SAVE_{i,j,q} \le FLOW_{i,j,q} \qquad \forall (i,j) \in R, q \in Q \qquad \text{(DF3) } [\gamma]$$

$$SAVE_{i,j,q} \le (u_{i,j} + \left[x_{i,j} \right]_{(i,j)\in P}) defend_{i,j,q} \qquad \forall (i,j) \in R, q \in Q \qquad \text{(DF4) } [\delta]$$

$$FLOW_{i,j,q} \ge 0 \qquad \forall (i,j) \in A, q \in Q \qquad \text{(DF9)}$$

$$SAVE_{i,j,q} \ge 0 \qquad \forall (i,j) \in R, q \in Q \qquad \text{(DF10)}$$

(***DIVERT_FLOW***) is a linear program, and the square brackets to the right of each constraint define its dual variables. This permits us to reformulate the attacker-defender model into a conventional integer linear program:

Model

ATTACK_DIVERT:

$$\underset{\substack{ATTACKS\in \mathrm{A},\\ \alpha,\beta,\gamma,\delta}}{MIN} \quad \sum_{(i,j)\in R, q\in Q} \left(u_{i,j} + \left[x_{i,j} \sum_{\substack{q'\in\{i,j,q',d\},\\ q'+d-1\le q}} start_{i,j,q',d} \right]_{(i,j)\in P} \right) \beta_{i,j,q}$$

$$+ \sum_{(i,j)\in R, q\in Q} \left((u_{i,j} + \left[x_{i,j} \right]_{(i,j)\in P}) defend_{i,j,q} \right) \delta_{i,j,q}$$

$$- \sum_{q\in Q} \underline{spendpen}\, \underline{spend}_q - \sum_{q\in Q} \overline{spendpen}\, \overline{spend}_q \qquad \text{(AD0)}$$

$$s.t. \quad \alpha_{i,q} - \alpha_{j,q} + \beta_{i,j,q} - \gamma_{i,j,q} + v_{i,j} ATTACKS_{i,j,q} \ge 0$$

$$\forall (i,j) \in R, q \in Q \qquad \text{(AD7)} \ [FLOW_{i,j,q}]$$

$$\alpha_{t,q} - \alpha_{s,q} \ge 1 \qquad \forall q \in Q \qquad \text{(AD8)} \ [FLOW_{t,s,q}]$$

$$\gamma_{i,j,q} + \delta_{i,j,q} - d_{i,j} ATTACKS_{i,j,q} \ge 0 \ \ \forall (i,j) \in R, q \in Q \qquad \text{(AD9)} \ [SAVE_{i,j,q}]$$

$$\alpha_{s,q} = 0 \qquad \forall q \in Q \qquad \text{(AD10)}$$

$$\alpha_{n,q} \ unrestricted\ in\ sign \qquad \forall n \in N, q \in Q \qquad \text{(AD11)}$$

$$\beta_{i,j,q} \ge 0 \qquad \forall (i,j) \in R, q \in Q \qquad \text{(AD12)}$$

$$\gamma_{i,j,q} \ge 0 \qquad \forall (i,j) \in R, q \in Q \qquad \text{(AD13)}$$

$$\delta_{i,j,q} \ge 0 \qquad \forall (i,j) \in R, q \in Q \qquad \text{(AD14)}$$

Again, the square brackets at the right of each constraint denote its dual variable. $ATTACKS \in \mathrm{A}$ denotes the domain restrictions inherited from model (***ATTACK***), namely its constraints (A1)-(A6).

(***DIVERT_FLOW***) and (***ATTACK_DIVERT***) are separable by planning quarter if $ATTACKS \in \mathrm{A}$ is.

To complete our algorithm, we need one more result.

4. Lemma

Following Brown, et. al. [2005a], each Step 2) solution of (***FLOW***) offers a valid upper bound only if its fixed attack plan found by minimizing (AD0) is not constrained by (A5).

To illustrate this simplistically, represent defender capacity expansion and defense decisions and constraints by $y \in Y$, attacker decisions and constraints by variables $x \in X$, and ignore the flow variables and constraints seen by both defender and attacker. We are solving:

$$\max_{y \in Y} \min_{x \in X(y)} cy .$$

The notation $x \in X(y)$ denotes that the outer maximization solution *y* influences the inner constraint set and domain of *x*. The following relationships are immediate:

$$\max_{y \in Y,\, y \text{ fixed}} \min_{x \in X(y)} cy \le \max_{y \in Y} \min_{x \in X(y)} cy \le \max_{y \in Y} \min_{x \in X(y),\, x \text{ fixed}} cy .$$

The former inequality is valid because the right-hand maximization is a relaxation of the left-hand one. The latter inequality is valid because the left-hand minimization is a relaxation of the right-hand one.

These global lower and upper bounds hold as transitive inequalities for any admissible solutions to this problem, as long as the domain restrictions on admissibility of the variables remain invariant.

Our algorithm generates a sequence of solutions, each featuring a new restriction in addition to $x \in X$ (i.e., *x* is also restricted to be distinct from any prior one by a diversity constraint (A5)). The upper bound at the far right is admissible if the central minimization is a relaxation of the one on the far right and if the domain $x \in X(y)$ remains invariant. If no constraint (A5) is taut for such an *x*, this is the case. QED.

The tri-level, defender-attacker-defender optimization proceeds as follows.

1) Initialize the current attack plan to have no attacks. Set iteration *c*=0.
2) Given the current attack plan, solve the defender mixed integer program (***FLOW***), yielding a complete capital expansion, defense, and oil export plan for the planning horizon.

3) This defender plan assumes perfect knowledge of a fixed current attack plan, and is thus optimistic. Under the lemma conditions, the value of (F0) provides an upper bound on the highest net oil export achievable.
4) Given the defender plan, solve the bi-level integer linear program (***ATTACK_DIVERT***) for a set of attacks that differs in at least one detail from each of the *c* prior, legacy attack plans, and for a set of dual variables representing the simultaneous, responding flow re-planning.
5) With the capital expansion and defense plan from step 2) fixed, and attacks from step 4) fixed, solve the linear program (***FLOW***) to recover arc flows.
6) This revision provides a candidate plan that may be the lowest net oil export achieved. Increase $c = c + 1$, and record the revised, current attack plan as the c-th legacy plan.
7) Repeat Steps 1) to 6) until the gap between the highest and lowest net oil export is sufficiently small, or until reaching some iteration limit.
8) Recover the best legacy capital expansion, defense, attack, and flow plan discovered.

This is a strategic capacity planning model – an engineering model – not a model of two-sided military conflict. We assume that the attacker can sustain interdictions at the rates specified quarter-after-quarter, over the entire planning horizon. We can introduce counter-attacks that attrite the attacker's capabilities. To make this operational embellishment, which is not difficult, we recommend solving this capacity expansion, defense, and counter-attack model quarterly, with quarter-to-quarter revisions of the state of attacker and defender. Brown and Washburn [2000] present a detailed example of how to manage such an iteration for a full-scale theater war.

III. ESTIMATING COSTS

Too many people in and outside of Iraq are hoping to deny Iraq a better future through a campaign of sabotage and plunder of the country's neglected oil facilities… The joint success of Americans and Iraqis to rebuild Iraq depends on the ability to bring the country's crude back online.

Gal Luft,
Director of the Institute for the Analysis of Global Security

A. OVERVIEW

We estimate all of the construction costs, construction durations, penalties and defense effectiveness factors reported here. There is not an open literature source detailing the type of data required to build a highly accurate project cost and duration estimation model. There are, however, proprietary sources that typically cost $600 to $3000 each and include technical site surveys and field reports. In addition, there are several engineering and consulting firms who specialize in these subjects and claim expertise and first-hand knowledge of Iraq's oil sector and the region's oil construction industry.

Instead of proprietary sources, we rely upon the U.S. Army Corps of Engineer's historical data and cost estimating factors for similar projects as the starting point for our estimation. We believe that we have developed reasonable, rough order-of-magnitude estimates of the real cost; and that if the real and expected costs differ by some common factor, this will not impact the overall qualitative outcome of our planning.

B. ESTIMATING PIPELINE CONSTRUCTION COST

1. Characterizing the Iraqi Crude Oil Distribution Network by Flow Capacity, Node Location and Arc Distances

Using Organization of the Petroleum Exporting Countries (OPEC) reports, various maps from the National Imagery and Mapping Agency (NIMA) and other public sources, as well as news reports concerning Iraq's oil industry, we nominate a compact list of sixty-three primary nodes (see Appendix A) The flow capacities into and out of each of these nodes is based, in most cases, on nameplate information, rather than on a mathematical function of pipe diameter, pump station size, or any other combination of factors. Because of varying oil viscosities, pumping station configurations and use of various drag reducing agents that are added to aid in-transit oil flows, the mathematical functions needed to describe flow capacity are overly complicated. We accept published values.

In those instances where a new pipeline might be constructed, the diameter and flow capacity is assumed to be equal to its previous historical value (if it was an abandoned or previously surveyed line), or estimated to be equivalent to another comparably-sized segment in the network. For example, we estimate the second north-south pipeline to be of the same diameter and flow rate as the existing north-south line extending from the K-3 pump station at Haditha to Zubair.

The pipeline nodes are not located with exact geographical precision, though the four-decimal place latitude and longitude coordinates provided in Appendix A might suggest otherwise. We use a map to view the areas of greatest interest and to identify the major oil producing regions and infrastructure. Then, where a city or significant geographic feature can be specified by name, we use internet-based tools to determine a reasonably precise location (e.g., www.heavens-above.com [Peat, 2005]). Finally, we verify our coordinates using imaging tools that are capable of importing scaled digital maps and reporting the approximate geographic location of a map feature. The tool we used is a simulation package called DIAMOND [DMSO, 2005], but there are several others with similar features.

We calculate the lengths of each pipeline segment in nautical miles using the great circle formula and the spherical earth model in which one nautical mile subtends one minute of an arc created by the earth's surface ($1' = 1nm = 1/60th\ degree$). These distances are shown in Appendix B. The calculation is as follows:

Great-Circle Distance:

$$d(\delta_1, \rho_1, \delta_2, \rho_2) = \cos^{-1}\left(\sin\delta_1 \sin\delta_2 + \cos\delta_1 \cos\delta_2 \cos(\rho_1 - \rho_2)\right)$$

this is mathematically equivalent to :

$$= 2 * \sin^{-1}\left(\sqrt{\left(\sin\left((\delta_1 - \delta_2)/2\right)\right)^2 + \cos(\delta_1) * \cos(\delta_2) * \left(\sin\left((\rho_1 - \rho_2)/2\right)\right)^2}\right)$$

Example:

Compute the distance between the Rumaila oil field (Latitude~30.5333N, Longitude~ 47.5000E) and the Zubair oil hub (Latitude~30.2756N, Longitude~48.1551).

$$\begin{aligned}
\delta_1 &= 30.5333/(180*\pi) = 0.0540\ radians \\
\delta_2 &= 30.2756/(180*\pi) = 0.0535\ radians \\
\rho_1 &= 47.4500/(180*\pi) = 0.0839\ radians \\
\rho_2 &= 48.1551/(180*\pi) = 0.0852\ radians
\end{aligned}$$

$$\begin{aligned}
d &= \cos^{-1}\left(\sin(\delta_1) * \sin(\delta_2) + \cos(\delta_1) * \cos(\delta_2) * \cos(\rho_1 - \rho_2)\right) \\
&= \cos^{-1}\left(\sin(0.0540) * \sin(0.0535) + \cos(0.0540) * \cos(0.0535) * \cos(0.0839 - 0.0852)\right) \\
&= \cos^{-1}(0.9999) \\
&= 0.0115\ radians \\
&= (0.0115 * 180 * 60)/\pi\ \ nm \\
&= 39.6286\ nm \\
&\approx \lceil 39.6286 \rceil = 40\ nm
\end{aligned}$$

2. Estimating New Construction Costs and Their Relationship to the Cost of Improving an Existing Pipeline

We base new pipeline costs on regression results derived from the data contained in the U.S. Army Corps of Engineer's *Pax Newsletters 3.2.1* and *3.2.2* [Ghosh, 2005b and 2005a respectively]. Each of these newsletters is an update to the cost estimation

procedures outlined in the Army's *Programming Cost Estimates for Military Construction* technical manual [U.S. Army, 1994].

In Pax Newsletter 3.2.2 [Ghosh, 2005a], the Army Corps of Engineers (ACE) categorizes a wide spectrum of potential military construction projects by cost per unit quantity based on the Army's historical construction award data. In particular, Chart A to Appendix A of the newsletter discusses sitework and utility construction using welded steel piping comparable to that used in petroleum pipelines. For sitework and utilities the ACE identifies 9 different cost estimates for procuring and assembling schedule-40 black steel pipe with diameters ranging from 1 to 24 inches (see Table 1).

Figure 3. Finished pipelines in Iraq are constructed of schedule-40 black steel and assembled in 40-60 foot sections for above-ground use. [SPG Media Limited, 2005]

Diameter (inches)	Cost of Pipe ($ / LF)
1	$ 12.20
2	17.60
3	21.80
4	27.00
6	33.10
10	72.20
12	103.10
18	136.00
24	231.80

Table 1. **U.S. Army Historical Pipe Cost Data.** These are the Army's historical costs per linear foot ($/LF) to furnish, assemble and install schedule 40 black steel piping. Trenching, bedding, backfill and compaction – if required – must be added to these costs. For example, a standard 40 foot length of 24 inch diameter piping, is expected to cost 40 x 231.80 = $9,272 to procure, stage and weld into place.

We categorize pipes by diameter as small (18"), medium (32"), or large (>45"). The sizes of each arc in the Iraqi oil network are shown in Appendix C. The larger two sizes of pipelines – while typical within the oil industry – fall outside the range of the Army's available historical data for steel pipe construction. So, we extrapolate.

We estimate pipeline construction costs using two different regression models using the data shown in Table 1. Each is represented as a single variable function of the pipe's diameter. Boyle [2002] et. al., describes other cost estimation techniques, but requires knowledge of specific physical and geographical factors that are not readily obtainable for Iraq.

Calculation of Simple First-Order Model:

Table 2 shows the model we use to estimate the costs of pipelines up to 45 inches in diameter. For pipelines larger than 45 inches, we use a second-order polynomial model because it produces a much steeper increase in cost per linear foot that reflects the difficulty of procuring, staging and assembling large-diameter steel piping.

Summary			Confidence Ints.			
			Level	0.95	R^2	0.969047
	Estimate	SE	Lower	Upper	s	13.81914
Slope	9.159065	0.6187	7.69608	10.6221		
Constant	-8.658352	7.17382	-25.622	8.30502		

Table 2. **Summary of Pipeline Results Using First-Order Regression.** This figure summarizes the results of a simple first-order regression used for ‘small’ and ‘medium’ sized pipes. The estimate column lists the coefficients for the linear model (y = a + bx), where ‘y’ is the estimated cost, ‘a’ is the constant coefficient, ‘b’ is slope coefficient, and ‘x’ is the diameter of the pipe in inches. The other values are qualitative expressions supporting the linear model and are standard statistical terms [e.g., see Montgomery, et. al., 2001, pp. 13-39]. SE is the standard error of the coefficients. ‘s’ is the standard error of the residuals. The coefficient of determination (R^2) and the upper- lower-bounds on the confidence interval will be explained in greater detail below.

Hypothesis Tests	
Slope	**Constant**
H_0: Slope = 0	H_0: Const = 0
Alternative: ○ ≠ ◉ > ○ <	Alternative: ○ ≠ ○ > ◉ <
H_1: Slope > 0	H_1: Const < 0
p-value = 7.69E-07	p-value = 0.133327

Table 3. **Summary of Pipeline Hypothesis Testing Using Simple First-Order Regression.** The first test evaluates the assertion that the slope of the true regression is zero (H_0) versus the alternative that it is greater than zero (H_1). We see that the probability of H_0 being true is very low (p-value = 7.69E-07) and we reject it at a significance level of α=0.05. The second test evaluates the probability that the constant (or intercept) of the line is 0 (H_0), or something less than 0 (H_1). Based on a p-value = 0.13 we do not reject H_0 at the 0.05 significance level and conclude that forcing the line through the origin is one acceptable model.

Simple First-Order Model: $\text{Cost}\ \left(\$/\text{LF}\right) = 9.159 \cdot \text{Diam (in)}\ - 8.658$

Tables 2 and 3 summarize our simple first-order model and highlight the qualitative terms we use to verify the "goodness" of the regression. The coefficient of determination (R^2) in Table 2 is very reasonable and indicates that the model describes 96.9% of the variability in cost with just the diameter of the pipe as a predictor [e.g., Montgomery, et al., 2001, pp. 39]. There are also two hypothesis tests shown in Table 3 respectively for the slope and constant (or intercept) terms. These are standard statistical tests. The first indicates with a high degree of certainty (~100%) that the true slope is greater than zero – i.e. costs increase with diameter. The second test concerns where a regression intercepts the y-axis. The hypothesis test concludes that it is not an unreasonable assumption to force the line through the origin, however, allowing a negative value at the extreme lower end of the regression contributes to a steeper overall slope in the first-order model. We believe a steeper slope is desirable to better facilitate a switch over to a second-order polynomial equation at large pipe diameters. The end result is this produces closer agreement between the two models at the point of transition.

Figure 4 shows a graph of the linear model describing the cost per linear foot of pipes up to 60-inches in diameter. The diamonds indicate the Army's historical costs for pipe of those sizes. Above and below the solid line (the fitted values) are the 95% confidence interval (CI) and prediction intervals (PI) respectively. (For reference, the prediction bands are the furthest from the best-fit line and are drawn slightly outside of the confidence bands.) The 95% prediction interval is the area in which you expect 95% of all individual data points to be observed. In contrast, the 95% confidence interval is the region that has a 95% chance of containing the true regression line [e.g., Montgomery, et. al., 2001, pp. 32-39].

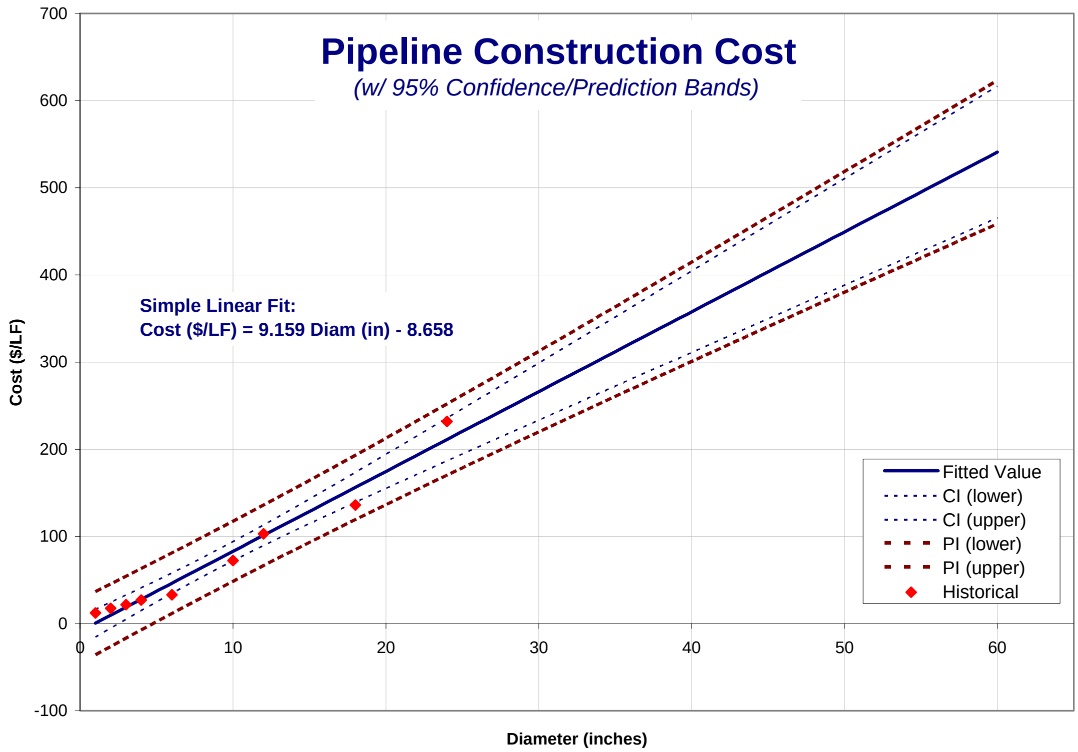


Figure 4. **Fitted Values for First-Order Pipeline Model with 95% CI and PI Bounds Indicated**. This represents pipeline costs per linear foot as a function of diameter. Per the solid center line, a 32-inch pipeline is expected to cost ~$284 per linear foot. However, the 95% confidence interval for this regression line indicates that the pipe's true cost might realistically fall between $249 and $320 per linear foot. If enough observations were available, the 95% prediction bounds indicate that single point estimates for the cost of a linear foot of pipe can be observed as low $236 and as high as $332 per linear foot.

The overall fit of the data in Figure 4 appears to be reasonable; and at a 45-inch diameter the upper and lower bounds on the prediction interval are not more than ±15% of the model estimate. Table 4 provides a sample of five values taken from the above graph.

Bounds on the Estimate		C.I. for Cost ($/LF)		P.I. for Cost ($/LF)	
		Level	0.95	Level	0.95
Diam (in)	Cost ($/LF)	Lower	Upper	Lower	Upper
0	(8.658)	(25.622)	8.305	(45.476)	28.159
18	156.205	138.991	173.419	119.271	193.139
32	284.432	248.909	319.954	236.165	332.698
45	403.500	349.558	457.441	340.432	466.567
48	430.977	372.730	489.223	364.190	497.763

Table 4. **Upper and Lower Bounds on Pipeline Construction Cost Estimates Using Simple First-Order Model.** Using a 45-inch diameter pipe as an example, we estimate the base cost to be $403.50 per linear foot. The 95% confidence interval predicts that the true regression estimate might really be as high as $457.44 and as low as $349.56 per linear foot (±13.4%). On the other hand if we could look at more historical data on 45-inch pipeline construction we would not expect the project costs for these new observations to cost more than $466.57 or less than $340.43 per linear foot. (±15.6%).

Calculation of Second-Order Polynomial Model:

We use a second-order polynomial equation for pipe sections larger than 45 inches. We adopt this to reflect empirical evidence that at larger diameters the pipe's wall thickness, weld times, and structural enhancements all contribute towards a super-linear increase in pipe cost. The Army's historical data does not cover the full range of pipe sizes, so there is uncertainty where the best transition between the simple first-order model and the second-order polynomial model should occur. At 30 inches diameter the first-order model begins to predict fitted values that are below the 95% prediction bound of the second-order model. We require cost estimates for diameters up to 60 inches, so we assign the change-over between equations at the midpoint between 30 and 60 inches.

The results of the second-order polynomial regression are presented in Table 5.

Summary			Confidence Ints.			
			Level	0.95	R^2	0.988
	Estimate	SE	Lower	Upper	s	9.22
Constant	7.087	6.957	-9.935	24.109		
Diam (in)	4.349	1.597	0.443	8.256		
Diam (in)^2	0.201	0.064	0.043	0.359		

Table 5. **Summary of Pipeline Construction Cost Estimates Using Second-Order Polynomial Fit.** This figure summarizes the results of the second-order polynomial regression used for 'large' pipelines (>45 inches). The estimate column shows the coefficients for the second-order polynomial model ($y = a + bx + cx^2$), where 'y' is the estimated cost of pipe per linear foot, 'a' is the constant coefficient, 'b' is the first-order term for the slope, 'c' is the second-order term, and 'x' is the diameter of the pipe in inches. The other values are qualitative expressions supporting the non-linear model and are comparable to those discussed in Table 2 and most statistical texts [Montgomery, et. al., 2001, pp. 221-228].

Second Order Polynomial: $\text{Cost } (\$/\text{LF}) = 7.09 + \left[4.35 \cdot \text{Diam (in)}\right] + \left[0.2 \cdot \text{Diam (in)}\right]^2$

Using the above equation, we estimate the cost for a 48-inch pipeline – similar to those connecting Rumaila with Zubair and Zubair with Saudi Arabia – to be $\left[7.087 + 4.349(48) + 0.201(48)^2\right] \cong 679$ dollars per linear foot of pipe. This is an increase of 57% over the cost predicted by the first-order model, but is actually much closer to the true cost experienced by oil companies building larger diameter pipelines [Boyle, 2002].

Figure 5 shows the predicted costs of a pipeline using the second-order polynomial equation. Similar to Figure 4, the 95% confidence and prediction bands in Table 6 provide representative values for the fitted, confidence bands and prediction bands to the graph below.

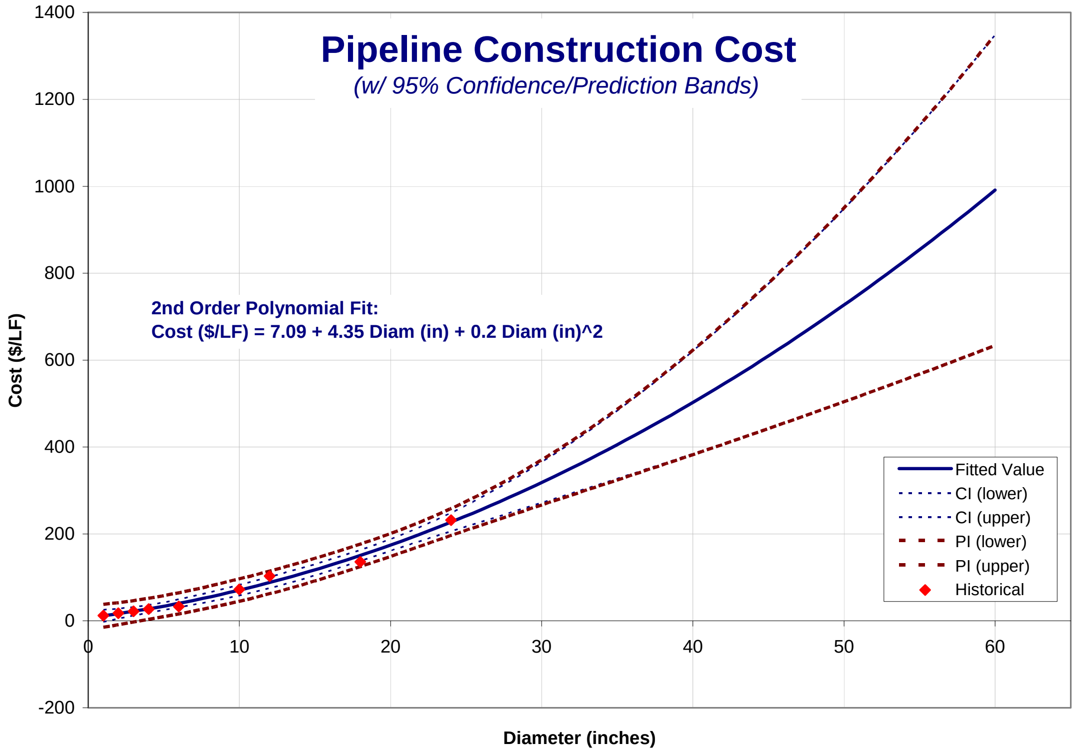


Figure 5. **Second-Order Polynomial Model with 95% CI and PI Bounds Indicated**. This estimates pipeline costs per linear foot as a function of diameter. A 48-inch pipeline is estimated to cost ~$679 per linear foot However, the 95% confidence interval for this regression line indicates that the pipe's true cost is between $480 and $877. Also, if enough observations were taken, the 95% prediction bounds on the point estimates for the cost of one linear foot of pipe would be between $478 and $878.

Because of the second-order term in the second-order model, the increase in separation between the fitted values and the confidence and prediction bands increases more rapidly than in Figure 4. This is normal for a second-order model [e.g., Devore, 2004, pp. 581-583.] and results in possible variances in pipe costs no greater than ±29.4%.

Bounds on the Estimate		C.I. for Cost ($/LF)		P.I. for Cost ($/LF)	
		Level 0.95		Level 0.95	
Diam (in)	Cost ($/LF)	Lower	Upper	Lower	Upper
0	7.087	(9.935)	24.109	(21.174)	35.348
18	150.462	137.753	163.172	124.569	176.355
32	351.979	293.584	410.374	289.378	414.580
45	609.617	443.672	775.562	442.145	777.089
48	678.715	480.232	877.198	478.954	878.476

Table 6. **Upper and Lower Bounds on Pipeline Construction Cost Estimates Using a Second-Order Polynomial Fit.** Using a 48-inch diameter pipe as an example, we compute the base cost to be $678.72 per linear foot. The 95% confidence interval predicts that the true regression estimate might really be as high as $877.20 and as low as $480.23 per linear foot (±29.2%). On the other hand if we could look at more historical data on 48-inch pipeline construction we would not expect the project costs for these new observations to cost more than $878.48 or less than $478.95 per linear foot. (±29.4%).

Incorporation of Area Cost Factors:

In Pax Newsletter 3.2.1 [Ghosh, 2005b] the Army Corps of Engineers provides Area Cost Factors (ACF) used for adjusting cost estimates based on the relative availability of labor, materials and equipment for a specific region of the world. The ACF for Iraq is currently set in Table B of the newsletter at 1.71 [Ghosh, 2005b]. This means a $100 million project at a location with an ACF of 1.0 is estimated to cost $171 million in Iraq.

Relationship between new construction and upgrades to an existing system:

We estimate the cost of upgrading an existing but degraded oil pipeline to be 50% of the cost of a new construction. For example, we estimate the cost of upgrading the existing pipeline arc between the Rumaila oil field and the Zubair oil hub as $144.62 (CY07$M).

3. Estimating the Number and Costs of Pump and Booster Stations Along a Pipeline

Pumping stations are required to maintain static pressure in the pipelines over changes in elevation and distance. Using the configuration descriptions of several other

similar oil pipeline projects we find that on average pump and booster stations are built approximately every 144.8 km (90 mi). The equation we used for computing the number of pump stations is based exclusively on pipeline length and is as follows:

$$= IF\begin{cases}\left[\text{Arc Length}\right] > 30\text{ km, then } ROUND(\left[\text{Arc Length}\right]/144.8412\text{ km}),\\ \text{otherwise } 0)\end{cases}$$

We use data found in the U.S. Army Corps of Engineer's Pax Newsletters 3.2.2 [Ghosh, 2005a] to estimate the costs of these new pump and booster stations.

Figure 6. **Artist's representation of a typical pump station with ancillary facilities**. [SPG Media Limited, 2005]. Pump and booster stations similar to this are typically groupings of pumps operating in parallel. They are constructed approximately every 90 miles and their cost is a function of the expected flow capacity (gallons of oil per minute). This results in costs ranging from \$0.25 to \$9.8 million dollars per station in Iraq.

We apply a simple linear regression model based on the Army's historical data involving water pumping stations (category code 84472 of Appendix A, Part II) [Ghosh, 2005a]. These historical costs are provided in Table 7.

Capacity (gpm)	Unit Cost
500	$ 74,980.00
1000	99,530.00
2000	111,920.00
2500	115,230.00

Table 7. **U.S. Army Historical Water Pumping Station Cost Data.** This shows Army historical costs for a water pumping station at each indicated flow capacity. This price includes the cost to furnish, assemble and install each unit, and accounts for such items as the diesel drive, auto controls, and fittings and accessories. A complete pumping station usually has multiple pumping units mounted in parallel to accommodate the full flow volume of the pipeline.

Calculation of Simple Linear Model:

Table 8 summarizes the results of a simple first-order regression using the data in Table 7.

Summary			Confidence Ints.			
			Level	0.95	R^2	0.86
	Estimate	SE	Lower	Upper	s	8,267.90
Constant	72,548.00	8,866.34	34,399.19	110,696.81		
gpm	18.58	5.23	(3.92)	41.08		

Table 8. **Pump and Booster Station Costs Using Simple First-Order Regression.** This figure summarizes the results of a simple first-order regression. The estimate column lists the coefficients for the first-order model (y = a + bx) used for calculating the cost of a water pumping station. The other values are qualitative expressions supporting the first-order model and are similar in description to those values discussed in Table 2, and in statistical texts [Montgomery, et. al., 2001, pp. 13-39].

Simple Linear Model: $\text{Cost }(\$) = 18.58 \cdot \text{Flow (gpm)} + 72{,}548.00$

Table 8 summarizes the basic first-order model and highlights the qualitative terms we use to verify the "goodness" of the regression. The coefficient of determination (R^2) is not particularly high and indicates that the model only describes 86% of the variability in cost when using gallons-per-minute (gpm) as the predictor variable [e.g., Montgomery, et al., 2001, p. 39]. The confidence intervals of this regression reveal

significant uncertainty (±53% on the constant and ±121% on the slope). This is because of the small number of data points available from which to base the regression.

Figure 7 and Table 9 show the fitted values of a second-order polynomial regression in relation to the computed 95% confidence and prediction intervals. We see that a simple doubling of flow rates from 2,500 to 5,000 gpm increases costs by a much as 246% (between the lower extreme and the higher extreme of the two pump capacities) based on the uncertainty intrinsic to this model.

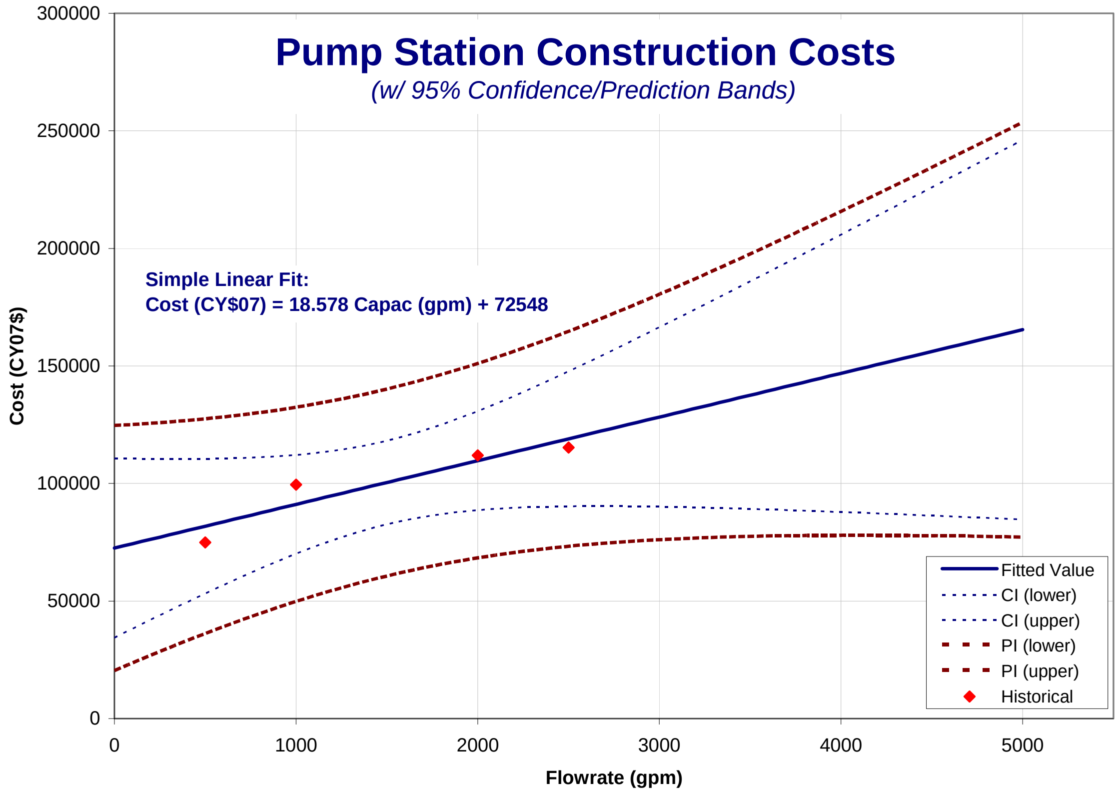


Figure 7. **First-Order Pump Station Cost Model with 95% CI and PI Bounds Indicated**. This estimates pump station costs as a function of gallons-per-minute of flow capacity. For example a pump station with a flow rate of 2,500 gpm has a base cost of $72,548 (based on the intercept), plus an additional $46,445 associated with the capacity of the pumps. The 95% confidence and prediction bands indicate the range of values realistically possible for the true regression line and individual observations respectively.

Bounds on the Estimate		C.I. for Cost ($/LF)		P.I. for Cost ($/LF)	
		Level	0.95	Level	0.95
Flow (gpm)	Cost ($/LF)	Lower	Upper	Lower	Upper
0	72,548.00	34,399.22	110,696.78	20,386.39	124,709.61
500	81,837.00	53,156.39	110,517.61	36,141.47	127,532.53
1000	91,126.00	70,080.18	112,171.82	49,792.84	132,459.16
2500	118,993.00	90,312.39	147,673.61	73,297.47	164,688.53
5000	165,438.00	84,707.92	246,168.08	77,217.54	253,658.46

Table 9. **Upper and Lower Bounds on Pump Station Construction Cost Estimates Using Simple First-Order Model.** Using a 5,000 gpm pump as an example, we compute the base cost of each station to be $165,438. The 95% confidence interval predicts that the true regression estimate is realistically between $84,708 and $246,168 (±48.8%). On the other hand, if we could look at more historical data on this size of pump we would not expect the project costs for these new observations to cost more than $253,658 or less than $77,218 each (±53.3%).

When building a relatively short pipeline, the cost of a single pumping station can double the total cost of the project. However, based on the average maximum capacity and pipeline length in the Iraqi crude oil distribution network, pump stations only account for 20% of the total cost of a typical Iraqi expansion project.

Accounting for differences between water and crude oil pump stations:

Pumping oil is not the same as pumping water. The viscosity of crude oil is much higher and petroleum presents additional concerns such as venting gas, etc. We assume the cost of building an oil pumping station to be twice as much as a water pumping station and apply a *pump complexity factor* of 2.0 to all pump station estimates. A water pumping station, for example, that costs $630,000 each, inflates to an oil pumping station costing $1,260,000 each.

C. ESTIMATING THE TIME TO COMPLETE A PROJECT AND THE COST OF ACCELERATING ITS COMPLETION

Every project requires some amount of planning time to survey the routes, analyze the physical requirements of the network, order materials and stage them, etc. We assume that because the majority of eligible Iraqi projects are for existing or abandoned pipelines, much of the engineering analysis required is already available. We

also assume a very high degree of national will on the part of the Iraqi government to see these projects through to completion once a decision is made to begin. In consideration of the significant benefits to be gained from the early completion of some projects we consider the possibility of accelerating (also referred to as "crashing") them whenever this is feasible and cost effective.

We compute normal project durations as follows: a fixed project planning time [time] + (pipeline length [distance]/speed of advance [distance/time])*pipe size factor [unitless] + (number of pump stations [EACH]/pump station construction rate [EACH/time]) = duration [time].

Crashing a Construction Project:

Crashing a project increases estimated costs by 20% per quarter of reduced duration. The methods used for calculating these project durations are based on historical project data.

1. Assumptions Regarding a Normal Duration Project

We assume a planning period of 14 days per 62 mi of pipeline + (40 mi/month base rate of advance) times a pipe size factor (1.0 for pipes <= 18", 1.1 for pipes > 18", and 1.2 for pipes >45") + 30 days per pump station. Any fraction of a quarter is rounded up.

2. Assumptions Regarding Crashing a Project

We assume a planning period of 21 days per 62 mi of pipeline + (81 mi/month base rate of advance with double the workforce) times a pipe size factor (1.0 for pipes <= 18", 1.1 for pipes > 18", and 1.2 for pipes >45". There is no pump station penalty. Any fraction of a quarter is rounded up.

D. A COMPARISON OF OUR COST ESTIMATES WITH OTHER PIPELINE PROJECTS

When we compare our cost estimates against three other well-known pipeline projects, we find our approximations to be very reasonable. For the purpose of standardization, all cost estimates are adjusted for inflation to a base year of 2007 using Navy military construction purchasing indices [U.S. Navy, 2005].

1. Trans-Afghanistan Pipeline

In 1998 UNOCAL obtained construction contracts for the Trans-Afghanistan Pipeline that authorized the engineering design and first stages of construction for what proponents of the project called a modern continuation of the “Silk Road”. Two years later UNOCAL pulled out after the Taliban became unmanageable. The total cost of this project is estimated today at $3 billion ($FY05) [Wikipedia, 2005].

Length:	1040 miUS = 5,491,200 ftUS
Diameter:	42”
Capacity:	1.0 mbbd ~ 30,000 gpm
Pump Stations:	12
Pump Station Complexity Factor:	2.0
Published Cost:	2.5B (FY98$) and 3.0B (FY05$)
Area Cost Factor (ACF):	1.5 (Afghanistan)
Project Complexity Factor:	1.0

Table 10. **Characteristics of the Trans-Afghanistan Pipeline.** Because pipe size is less than 45” we use the simple first-order model to calculate a pipe cost of $376 per linear foot. The capacity of the pipeline is 1.0 mbbd and equivalent to approximately 30,000 gpm rounded up. Using this value we compute each pump station to cost $1.3 million (including a 2.0 oil-rather-than-water cost inflation). An ACF of 1.5 is applied to the sum total of pipe and pumping station costs. Lastly, a project complexity factor of 1.0 – indicating the project is of the same complexity in terms of geography and engineering efforts required as that of pipelines in Iraq - is applied to the sum total of all costs to yield an estimated total of 3.12 (FY07$B) for the entire project.

Cost of Pipeline Construction:

$$\left[-8.66 + 9.16\left(42\text{" diameter}\right)\right] \cdot 5,491,200 \text{ ftUS} = 2.065 \quad \text{(FY07\$B)}$$

Cost of Pump Station Construction:

$$1040 \text{ mi arc length}/90\ [\text{mi / pump station}] = 11.56 \cong 12 \text{ pump stations}$$

$$\left[\left(72,548 + 18.58\left(30,000 \text{ gpm}\right)\right)\right] = \$629,888 \text{ each}$$
$$629,888 \cdot \left(12 \text{ pump stations}\right) \cdot \left(2.0 \text{ p/s complexity}\right) = 0.015\ \left(\text{FY07\$B}\right)$$

Accounting for Area Cost Factor:

$$\left(2.065 + 0.015\right) \cdot 1.5 = 3.12\ \left(\text{FY07\$B}\right)$$

Project Complexity Factor:

We use a project complexity factor as a circumspect adjustment to the total project cost to account for unique construction requirements such as burying a pipeline, providing unique external coatings or cathodic protection, or other unusual structural enhancements needed to traverse geographic features (bridges, tunnels, etc). A project complexity factor of 1.0 indicates that this project is considered comparable in complexity to a typical pipeline constructed in Iraq.

$$3.12\ \left(\text{FY07\$B}\right)\left(1.0\right) = 3.12\ \left(\text{FY07\$B}\right)$$

Comparison between our cost estimate and those published:

Normalizing the published cost of the project yields: \$3.0B (FY05) → \$3.12B (FY07), which is an exact match. Note that a different published estimate made by UNICAL in 1998 was \$2.5B that normalizes to \$2.9B (CY07). Assuming that the most recent estimate is really just a rounded approximation, the model is still within 8% of the earlier estimate.

2. Trans-Alaska Pipeline System

The 800-mile-long Trans Alaska Pipeline System is one of the largest pipeline systems in the world. It stretches from Prudhoe Bay on Alaska's North Slope, through rugged terrain, to Valdez, the northernmost ice-free port in North America. Since pipeline startup in 1977, the pipeline operator Alyeska Pipeline Service Company has successfully transported over 14 billion barrels of oil (Alyeska, 2005).

Length:	800 miUS = 4,224,000 ftUS
Diameter:	48”
Capacity:	2.0 mbbd ~ 60,000 gpm
Pump Stations:	12
Pump Station Complexity Factor:	2.0
Published Cost:	8.0 (FY77$B)
Area Cost Factor (ACF):	1.9 (Alaska)
Project Complexity Factor:	4.0

Table 11. **Characteristics of the Trans-Alaska Pipeline.** Because pipe size is greater than 45” we use the second-order polynomial model to calculate a pipe cost of $679 per linear foot. The capacity of the pipeline is 2.0 mbbd and equivalent to approximately 60,000 gpm rounded up. Using this value we compute each pump station to cost $2.4 million (including a 2.0 pump oil-rather-than-water cost inflation). An ACF of 1.9 is applied to the sum total of pipe and pumping station costs. Lastly, a project complexity factor of 4.0 is applied to the sum total of all costs to yield an estimated total of 22.0 (FY07$B) for the entire project.

Cost of Pipeline Construction:

$$\left[7.087 + 4.35(48") + 0.201(48")^2\right] \cdot 4,224,000 \text{ ftUS} = 2.868 \quad \text{(FY07\$B)}$$

Cost of Pump Station Construction:

$$800 \text{ mi arc length} / 90 \ [\text{mi / pump station}] = 8.89 \cong 9 \text{ pump stations}$$

However, 12 pump stations were built in 1977.

$$\left[\left(72,548 + 18.58(60,000 \text{ gpm})\right)\right] = \$1,187,228 \text{ each}$$

$$1,187,228 \cdot (12 \text{ pump stations}) \cdot (2.0 \text{ p/s complexity}) = 0.028 \ (\text{FY07\$B})$$

Accounting for Area Cost Factor:

$$\left(2.868+0.028\right)\cdot 1.9=5.50\ \left(\text{FY07\$B}\right)$$

***Accounting for Project Complexity*:**

$$5.50\cdot 4.0=22.0\ \left(\text{FY07\$B}\right)$$

The Alaska pipeline project was the first of its kind in 1977 and used the prevailing construction techniques and equipment available at that time. Along nearly half of it 800-mile length the pipeline is buried at depths ranging from 8 to 49 feet. Approximately 4 miles of the pipeline is refrigerated to prevent melting of the permafrost. The entire length of pipeline crosses 3 earthquake fault lines and is engineered to withstand the effects of earthquakes up to Richter magnitude 8.5. Additionally, a total of 13 bridges were constructed to traverse rivers and other geographic land formations. Based on the many added complexities unique to the Alaska pipeline, as well as accounting for the expected improvement in construction equipment and techniques since 1977, we assign a project complexity factor of 4.0.

Comparison between our cost estimate and those published:

Normalizing the published value yields: \$8.0B (FY77) → \$22.6B (FY07). By comparison, the cost estimation model predicts a cost of \$22.0B which is within 3 percent of the published value.

3. Baku-Tbilisi-Ceyhan Pipeline

The Baku-Tbilisi-Ceyhan (BTC) pipeline transports crude oil from the oil-rich Caspian region to the Turkish port of Ceyhan. The overland route obviates the need for 350 tanker cargos per year through the narrow and highly congested Bosporus sea lane. Along the way, the pipeline cuts across portions of three countries. Because of the high political instability of the regions traversed, the majority of the pipeline is buried and its eight pump stations fenced and provided additional security and surveillance (SPG Media, 2005).

Length:	445 km Azerbaijjan = 1,459,600 ftUS 245 km Georgia = 803,600 ftUS 1070 km Turkey = 3,158,640 ftUS (@ 42") + 350,960 ftUS (@ 32")
Diameter:	42" in Azerbaijjan 46" in Georgia 42" in Turkey (90% of pipeline) 32" in Turkey (10% of pipeline)
Capacity:	1.0 mbbd ~ 30,000 gpm
Pump Stations:	8
Pump Station Complexity Factor:	2.0
Published Cost:	2.9 (FY02$B), revised to 3.5-4.0 (FY05$B)
Area Cost Factor (ACF):	0.9 (Azerbaijjan) 0.9 (Georgia) 0.91 (Turkey)
Project Complexity Factor:	1.75

Table 12. **Characteristics of the Baku-Tbilisi-Ceyhan (BTC) Pipeline.** The BTC is the longest pipeline in the world and is comprised of multiple diameters of pipe. We estimate cost for all but 245 km using the first-order model. We use the second-order polynomial model for the rest. Capacity is a constant 1.0 mbbd and equivalent to 30,000 gpm rounded up. We compute the cost of each pump station to be $1.3 million (including a 2.0 oil-rather-than-water cost inflation). The ACF varies within each country but is approximately 0.9 and is applied to the sum total of pipe and pumping station costs. Lastly, a project complexity factor of 1.75 to the sum total of all costs to yield an estimated total of 3.75 (FY07$B) for the entire project.

Cost of Pipeline Construction:

$$\left[-8.66+9.16\left(42\text{" diameter}\right)\right]\cdot 1,459,600\text{ ftUS}=0.549\quad \textit{Azerbaijjan}$$
$$\left[7.087+4.35\left(46\text{"}\right)+0.201\left(46\text{"}\right)^2\right]\cdot 803,600\text{ ftUS}=0.508\quad \textit{Georgia}$$
$$\left[-8.66+9.16\left(42\text{" diameter}\right)\right]\cdot 3,158,640\text{ ftUS}=1.188\quad \textit{Turkey}$$
$$\left[-8.66+9.16\left(32\text{" diameter}\right)\right]\cdot 350,960\text{ ftUS}=0.100\quad \textit{Turkey}$$

$$\textit{Total}=2.345\ \left(\text{FY07\$B}\right)$$

Cost of Pump Station Construction:

There are 2 pump stations in Azerbaijjan, 2 in Georgia, and 4 in Turkey.

$$\left[\left(72,548+18.58\left(30,000\text{ gpm}\right)\right)\right]=\$629,888\text{ each}$$
$$629,888\cdot\left(8\text{ pump stations}\right)\cdot\left(2.0\text{ p/s complexity}\right)=0.010\ \left(\text{FY07\$B}\right)$$

Accounting for Area Cost Factor:

$$\left(0.549+0.00252\right)\cdot 0.9\cong 0.496\ \textit{Azerbaijjan}$$
$$\left(0.508+0.00252\right)\cdot 0.9\cong 0.459\ \textit{Georgia}$$
$$\left(1.188+0.00378\right)\cdot 0.91\cong 1.084\ \textit{Turkey}$$
$$\left(0.100+0.00126\right)\cdot 0.91\cong 0.100\ \textit{Turkey}$$

$$\textit{Total}=2.14\ \left(\text{FY07\$B}\right)$$

Accounting for Project Complexity:

$$2.14\cdot 1.75=3.75\ \left(\text{FY07\$B}\right)$$

The entire length of the pipeline has cathodic protection that adds 14% to the estimated cost [Ghosh, 2005a]. Additionally, the majority of the pipeline is buried at depths ranging from 3 to 30 feet (unlike the Iraqi pipelines which are currently built above ground) and this contributes an additional 50-60% in pipeline construction cost per linear foot. Finally, the cost of reimbursing citizens for right-of-way use is not accounted for in the Iraq cost estimates because the majority of Iraq’s pipelines either pre-exist or would be built over current rights-of-way. However, the companies building the BTC spent $133

million to acquire similar rights [SPG Media, 2005] and this adds an additional 6% to the total cost. Based on these additional circumstances, we assign a complexity factor of 1.75 to estimate the total cost.

Comparison between our cost estimate and those published:

Normalizing the published the 2002 value yields: \$2.9B (FY02) → \$3.52B (FY07). By comparison, the cost estimation model predicts a cost of \$3.75B which is within 7 percent of the published values.

E. EFFECTIVENESS OF INSURGENT ATTACKS AND THE MITIGATING EFFECTS OF DEFENSIVE MEASURES

1. The Penalty Cost (v_{ij}) Resulting From an Arc Attack

Our objective is measured in units of exported oil flow. Our penalty cost (or damage) following an attack on an arc in the network is expressed as a fraction of this export oil volume. This penalty depends on whether the arc represents a typical pipeline, a node, or an offshore terminal. A penalty value of zero indicates an invulnerable arc or node section, and no penalty can exceed 1.0, or total destruction. A value of 0.056 is equivalent to a 5-day stoppage over a 90-day planning quarter, and applies to attacks against normal above-ground pipeline sections. Pipelines are easy to repair and the duration of 5 days is consistent with recent experiences in Iraq using rapid repair teams. A value of 0.333 is equivalent to a stoppage of 30 days and applies to attacks against control valves and pumping stations, which are much more difficult to repair. 30 days assumes spare components are available or could be fabricated quickly. Offshore loading terminals are estimated to be the hardest to repair, and are set at 0.666 (equivalent to a loss of 60 days out of a 90-day planning quarter).

2. Defense Effectiveness (d_{ij}) for an Attacked Arc

Our defense effectiveness represents the fraction of oil flow at risk from an attack that is protected by a defense measure. For an arc with vulnerability 0.056, a defensive effectiveness of 0.022 corresponds to a 2 day (40%) reduction in the effectiveness of an

attack. For a pumping station with vulnerability 0.333, a defensive effectiveness of 0.333 corresponds to a 30 day reduction (100%) in attack effectiveness against a well-defended feature. Defensive actions to protect offshore terminals are also considered 100% effective.

A surface pipeline is long and vulnerable and a determined terrorist will presumably always succeed in blowing it up somewhere along its route. By comparison, the control valves, pumping stations and offshore terminals occupy a much smaller space and are easier to monitor, patrol and harden. Given sufficient defensive resources we believe these features can be sufficiently protected to either deter a would-be aggressor or to defeat actual attacks.

F. ESTIMATING DEFENSE COSTS

We estimate defense costs for pipelines to be $10,000 per mile per quarter. This is 10 times the cost Erinys, the first of several private security firms hired to protect Iraq's oil infrastructure, paid local tribesmen and trained Iraqi guards to do this job [Barazanji, 2004].

We estimate the cost of protecting pumping stations, control valves and other critical facilities as a function of maximum daily pumping capacity, and assign a cost of $100,000 per mbbl per day. For instance, the Zubair pumping station with an estimated daily flow rate of 6.2 mbbd costs $620,000 per quarter to defend.

G. CONSEQUENCES OF ELASTIC BUDGET CONSTRAINTS

If we require our investment budget to be spent exactly and uniformly -- quarter-by-quarter over our planning horizon -- then given the discrete investment and defense options available we will almost surely find no feasible solution. By allowing unavoidable under- and/or over-expenditures each quarter, albeit at some penalty per unit of such budget violation, we admit budget-feasible solutions. Then, by using cumulative budget constraints, any under- or over-expenditure accrues from one planning period to the next, and continues to exact penalties until expenditures retain the cumulative goal.

This reflects what project planners and managers actually do in practice when they need some budget flexibility to ensure continuity of operations.

In this model, the cumulative elastic budget violation penalties are very high -- they are essentially infinite for over-expenditures. As a result, the model has a predisposition to under spend. The penalty functions are set as follows in the optimization model:

$$
\begin{aligned}
lower\_penalty(q) = {} & 100000000.0 * (1000.0/1000000.0) * (1.0/oil\_price) \\
& * \exp(-0.02 * ((ord(q) - 1.0)/4.0))
\end{aligned}
$$

$$upper\_penalty(q) = \infty$$

Here, q is the ordinal planning quarter, and the lower penalty is inflated at a rate of 2% per year.

Both the upper and lower penalties are in kbbl of flow lost per million dollars over- or under-spent (i.e., oil export units per unit of budget violation).

IV. RESULTS AND INSIGHTS

A. DESCRIPTION OF SCENARIOS

We present five scenarios: *Baseline, Big Attack, Really Big Attack, Construction Cost Plus,* and *Defense Cost Plus*. Each scenario shares the same initial state of the network arcs, their starting material conditions, and the opportunity to construct new arcs and defend existing ones. We alter the first case, *Baseline,* by systematically changing scalar parameters shown in Table 13 to produce the remaining excursions. We use these parameters to define the scope and intensity of insurgent attacks, and the relative costs of construction and defense. Another parameter, *oil_price*, is set to $50 per barrel for all excursions. Although altering this has obvious effects on the conversion of oil export units into dollars, we are more interested in the allocation of available budget between construction and defense for various threat levels than in forecasting oil prices. If the price of oil varies, the affordable tempo of our plan changes, but the qualitative allocation of resources to re-build and/or defend oil infrastructure does not.

The key factors used in each run are summarized in Table 13.

Setting	Baseline	Big Attack	Really Big Attack	Construction Cost Plus	Defense Cost Plus
epoch_q	2	2	2	2	2
epoch_attacks	5	15	50	5	5
atks_by_q	10	15	30	10	10
mx_atks	300	500	500	300	300
atks_by_n_by_q	5	5	5	5	5
Construction factor	1.0	1.0	1.0	1.5	1.0
Defense factor	1.0	1.0	1.0	1.0	1.5

Table 13. **Summary of Key Model Parameters.** The first five italicized settings are control parameters that govern the frequency and intensity of insurgent attacks over the planning horizon, and the last two adjust construction and defense costs respectively as listed in Appendix D. In the *Defense Cost Plus* scenario, each arc may be attacked at most 5 times in any 2-quarter epoch of the planning horizon. There can be at most ten attacks per quarter on any arc, and at most 300 attacks over the entire 40-quarter planning horizon. In any planning quarter, all arcs incident to any given node may be attacked at most 5 times. Construction costs are not inflated, but defense costs are 150% of *Baseline*.

We define these settings as follows:

epoch_q **–** The length of time, in planning quarters, over which we wish to limit the number of insurgent attacks. We set *epoch_q* to 2 in each excursion presented, to represent that repeated attacks against any target over such a short time period results in better preparedness by the defenders.

epoch_attacks **–** The maximum number of times that a particular arc may be attacked in any epoch of *epoch_q* quarters. Increasing this parameter allows insurgents to attack an arc more frequently, however we assert that attackers cannot exceed it without alerting defenders to adapt and render the target essentially invulnerable. The scenarios *Big Attack* and *Really Big Attack*, respectively increase this number by 300% and 1,000% of *Baseline.*

atks_by_q **–** Maximum number of insurgent attacks per planning quarter. In the *Baseline* scenario we set this value at 10 and inflate it in *Big Attacks* and *Really Big Attacks* by 50% and 300% respectively.

mx_atks **–** The maximum number of attacks that may be conducted over the 40-quarter planning horizon. For *Baseline*, this is 300, or slightly more than the total number of real attacks conducted to date since 2003 [IAGS, 2005]. *Big Attacks* and *Really Big Attacks* increase this to 500.

atks_by_n_by_q **–** Limits the number of attacks that can be mounted against all adjoining arcs incident to any one model node. This shows how to limit the intensity of attacks on a small geographic area, where it is easier to mount joint defenses of adjacent arcs. We set this value at 5.

Construction factor – This term dictates by what factor we increase or decrease all construction costs. For instance, a factor of 1.5 increases construction costs shown in Appendix D by 50%.

Defense factor – This term dictates by what factor we increase or decrease defense costs. For instance, a factor of 1.7 increases defense costs shown in Appendix D by 70%.

$\overline{\boldsymbol{attacks}}_{\boldsymbol{i,j,q}}$ - This term is not shown in Table 14, but limits the attacks on each arc in each quarter. Reasoning that insurgents will not mount attacks that have no effect, we use this to limit attacks to a number that causes no more than 100% reduction of flow. This term can also be used to govern the number of attacks based on expert judgment.

We present these control parameters as simple examples for governing model behavior by, for instance, converting intelligence estimates into simple constraints that shape insurgent attacks. Because we model interdictions as an integer linear program, we can accommodate much more general guidance than this.

B. RESULTS FROM THE TRI-LEVEL OPTIMIZATION OF INDIVIDUAL SCENARIOS

Key outputs from the five optimizations are summarized in Tables 14, 15 and 16. We break these down into three areas – the contributions from defensive measures, the limits of defensive measures, and the contributions of capital expansion.

We ran each of the five scenarios in GAMS [GAMS, 2003] for 50 decomposition iterations using CPLEX 9.0 [ILOG, 2004] with a relative integer tolerance (OPTCR) set to 0.10. Each scenario requires approximately 3 hours to run on a 2 GHz Pentium 4 workstation with 1.0 GB of random access memory.

	Baseline	Big Attacks	Really Big Attacks	Construction Cost Plus	Defense Cost Plus
Arc/Nodes Attacked	292	496	499	293	292
Flow Lost (kbbl)	5,023,125	9,783,135	14,116,118	5,073,930	4,133,723
Arc/Nodes Defended	1,576	1,951	1,904	1,467	1,016
Flow Saved (kbbl)	-	336,699	775,170	990	-
Upper Bound (kbbl)	24,491,250	23,958,000	23,460,750	23,989,500	24,437,250
Achieved Flow (kbbl)	**23,856,750**	**23,067,000**	**23,222,250**	**23,548,500**	**23,193,000**
Lower Bound (kbbl)	16,728,288	9,910,773	3,856,921	17,055,746	18,021,990
Estimated Market Value ($M)	1,192,838	1,153,350	1,161,113	1,177,425	1,159,650

** Assuming price of oil is $50/barrel*

Table 14. **Summary of Attacks, Defenses, and Oil Exports.** The *Baseline* scenario suffers 292 attacks (out of a maximum of 300) during the 40-quarter planning horizon. These attacks prevent over 5 billion barrels of oil from reaching an export terminal, though 23.9 billion barrels do reach export destinations and have a market value of nearly $1.2 trillion. Over the planning horizon we defend 1,576 arc-quarters, but this results in no direct flow savings because the attackers, knowing our defense plans a priori, choose to attack undefended arcs: Insurgents may attack defended arcs, but in this case there are ample opportunities to attack undefended ones.

	Baseline	Big Attacks	Really Big Attacks	Construction Cost Plus	Defense Cost Plus
Full Expansion Cost (CY07$M)	4,468.06	4,468.06	4,468.06	6,702.09	4,468.06
Budget (120% Expansion Cost)	**5,361.67**	**5,361.67**	**5,361.67**	**8,042.50**	**5,361.67**
Expansion Costs (CY07$M)	4,076.07	4,076.07	4,076.07	6,527.39	4,721.81
Defense Costs (CY07$M)	662.24	763.43	843.18	594.14	610.70
Total Costs	**4,738.31**	**4,839.50**	**4,919.25**	**7,121.53**	**5,332.51**
Budget - Costs (CY07$M)	**623.36**	**522.17**	**442.42**	**920.97**	**29.16**

Table 15. **Summary of Construction and Defense Plans.** The budget for each scenario is estimated to be sufficient to fully expand the Iraqi oil distribution network, and is then inflated 20% to accommodate the cost of defenses and/or project acceleration. None of the five scenarios, including *Defense Cost Plus*, elect to complete all the candidate capacity expansion investments. Rather, the optimization applies the available funds to accelerate completion of key capacity expansion arcs. Each scenario dedicates about 12% of its total budget to defense, and this increases proportionally with the rise in insurgent activity. The unspent amounts on the bottom line are an artifact of our reluctance to allow any over-expenditure and the sheer size of the discrete investment options available. In reality, we would find some constructive way to use these funds.

All scenarios choose defensive measures to limit the effects of insurgent attacks. While each scenario achieves more than 6 million barrels per day in planned export capacity by the end of the 40-quarter planning horizon (see Appendix H for a detailed breakdown of the quarterly flow volumes achieved), the *Defense Cost Plus* scenario spends 50% more on defense, but schedules 709 fewer defense actions and suffers a 2.8% decrease in total flow in relation to *Baseline*. *Big Attacks* and *Really Big Attacks* also export less oil (an average decrease of 3.0%), but this decrease is small in comparison to the significant increases in attacks. An increase in defense costs permits fewer defense actions and inflicts the largest overall decrease in export potential: This appears to be a key exogenous factor.

Table 16 shows that, surprisingly, the net oil export difference between these five diverse scenarios is less than 3.5%. The ratio of attacks to defenses appears to be a good predictor of export success.

	Achieved Flow (total kbbl)	Attacks Conducted	Defense Actions	Percent Defended	Ratio of Atks/Def
Baseline	23,856,750	292	1576	0.540	0.185
Construction Cost Plus	23,548,500	293	1467	0.502	0.200
Really Big Attacks	23,222,250	499	1904	0.652	0.262
Defense Cost Plus	23,193,000	292	1016	0.348	0.287
Big Attacks	23,067,000	496	1951	0.668	0.254

Table 16. **Summary of Factors Contributing to Achievable Flow.** This table presents in descending order the amount of achieved export flow, and shows that the "percentage of arcs defended" is a poor indicator of future flow (i.e. the two lowest flow models have both the best and worst defense percentages). We consider the ratio of attacks to defenses the best of the 4 candidate predictors shown. Using this ratio as a basis for evaluating the 5 scenarios we predict that *Baseline* produces the highest flow and *Defense Cost Plus* produces the lowest. That *Big Attacks* is slightly more damaging than *Defense Cost Plus* (~0.5% less flow) does not change the overall conclusion that funding defensive measures is important. The difference in flow between both scenarios is less than the interval of uncertainty offered by our decomposition – that is, this difference is not large enough to be significant.

Figure 8 shows the inverse relationship between flow volume and the ratio of attacks to defenses. The dashed line represents the linear regression of the five data points, and we provide it as an indicator of the overall trend and not necessarily because we believe a linear relationship exists. But, we are confident that a continuation of the downward trend will occur with any increase in the ratio of attacks to defenses.

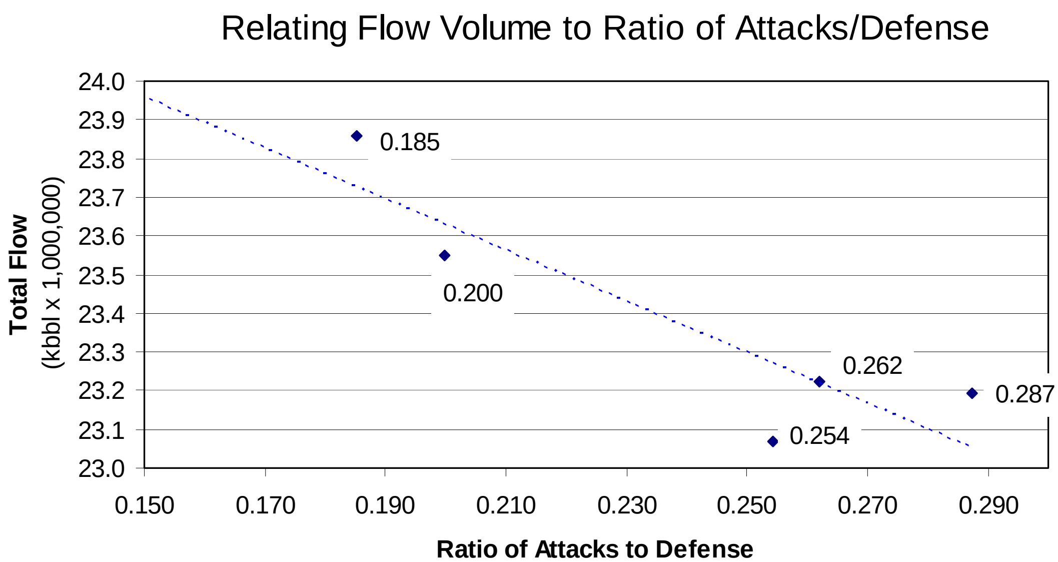


Figure 8. **Relating Flow Volume to the Ratio of Attacks to Defenses**. This illustrates the evident inverse relationship between total flow and the ratio of attacks to defenses. The dashed line represents the first-order regression of the five optimized scenario observations, but we show it merely as an indicator of the overall trend and not because we believe there is a particular linear relationship.

Given resources to defend "everything - all the time", the Iraqi network is by its design still vulnerable. Iraq's oil pipelines are hundreds of miles long, and all are built above-ground. These offer attractive target points virtually anywhere along their length. We acknowledge this vulnerability by assigning defense effectiveness factors ($d_{ij} \equiv 0.022$) to normal pipelines that do not fully offset the effects of an insurgent's attack ($v_{ij} \equiv 0.056$). Based on the optimal 40-quarter build profiles of our five scenarios (see Appendices I through M) we find that on average the Iraqi network only has 2,920 possible defense opportunities for the model to consider. This suggests that if the number of attacks is unconstrained, that in any scenario with imperfect defenses (i.e. $d_{ij} < v_{ij}$) when given enough attacks the benefits of "defending everything" can be overcome. Using the maximum of 2,920 possible defenses, we project that insurgents need only mount 876 attacks over the next 10 years, to achieve an attack to defense ratio of 0.30 - which is higher than any of the other scenarios presented thus far. If the present rate of

attacks in Iraq is sustained, conceivably the insurgents could mount over 1,000 interdictions in the next 10 years [IAGS, 2005].

Capacity expansion also provides system robustness against a sustained insurgent campaign. The expanded capacity and redundancy that is gained each quarter provides new targets for the insurgents, but also offers new degrees of freedom to respond to these attacks by redirecting flow. Figure 9 illustrates the maximum capacity of the fully-upgraded Iraqi oil network in quarter 40 if we do not allow new and/or redundant construction (~5.3 mbbd). This network can export 2.5 mbbd less flow than the *Baseline* model, and is completely interdictable by focusing attacks on the junctions at Zubair and Parallel (2) or upon the four pipelines indicated by the dashed line. By adding redundancy and additional capacity we create opportunities to redirect flow along uninterdicted arcs and to use larger residual capacity after attack damage is repaired. We observe this behavior in scenarios *Baseline* and *Defense Cost Plus* (Table 14) when attack intensity is moderate and construction rates are higher.

We provide a condensed view of the complete solution to the *Baseline* scenario over the 40-quarter planning horizon in Appendix N. The graphic focuses principally on the expansion of the pipeline (including capacity upgrades) and the distribution of attacks and defenses. Facilities and junctions are indicated only as references. Each pipeline is represented by a set of four numbers inside parentheses. These values indicate the following:

(X, - , - , -)	'0' indicates the pipeline is pre-existing. '1' indicates the pipeline is new construction.
(- ,X, - , -)	Indicates the quarter in which the pipeline is either upgraded or new construction begins. A value of '-' indicates no capital expansion project is initiated during the planning horizon.
(- , - ,X, -)	Indicates the number of quarters this particular pipeline is defended during the planning horizon.
(- , - , - ,X)	Indicates the number of times the pipeline is attacked. This value can not exceed *epoch_attacks*.

In the Baseline scenario, the optimization model consistently defends infrastructure across the board, but allocates the majority of its quarterly budget to

upgrading existing infrastructure. On average, the model defends each arc about once every two quarters over the 40-quarter planning horizon, and the attacks consistently chase the larger flows within the network. As new export routes are completed and flow rates dramatically increase, not surprisingly so do the frequency of attacks. Over a period extending from quarter 11 to quarter 25, the insurgents mount an average of 9.7 attacks per quarter (compared to an average of 3.7 during the previous 10 quarters). By quarter 18, the balance of export flow that now primarily leaves the country through southern terminals returns to a more even distribution among the nine export points. In all five scenarios, the percentage of oil leaving the country through the two offshore loading facilities (frequent targets for the model) is decreased from 90% (Feld, 2005b) to a more flexible and defendable 40-45%.

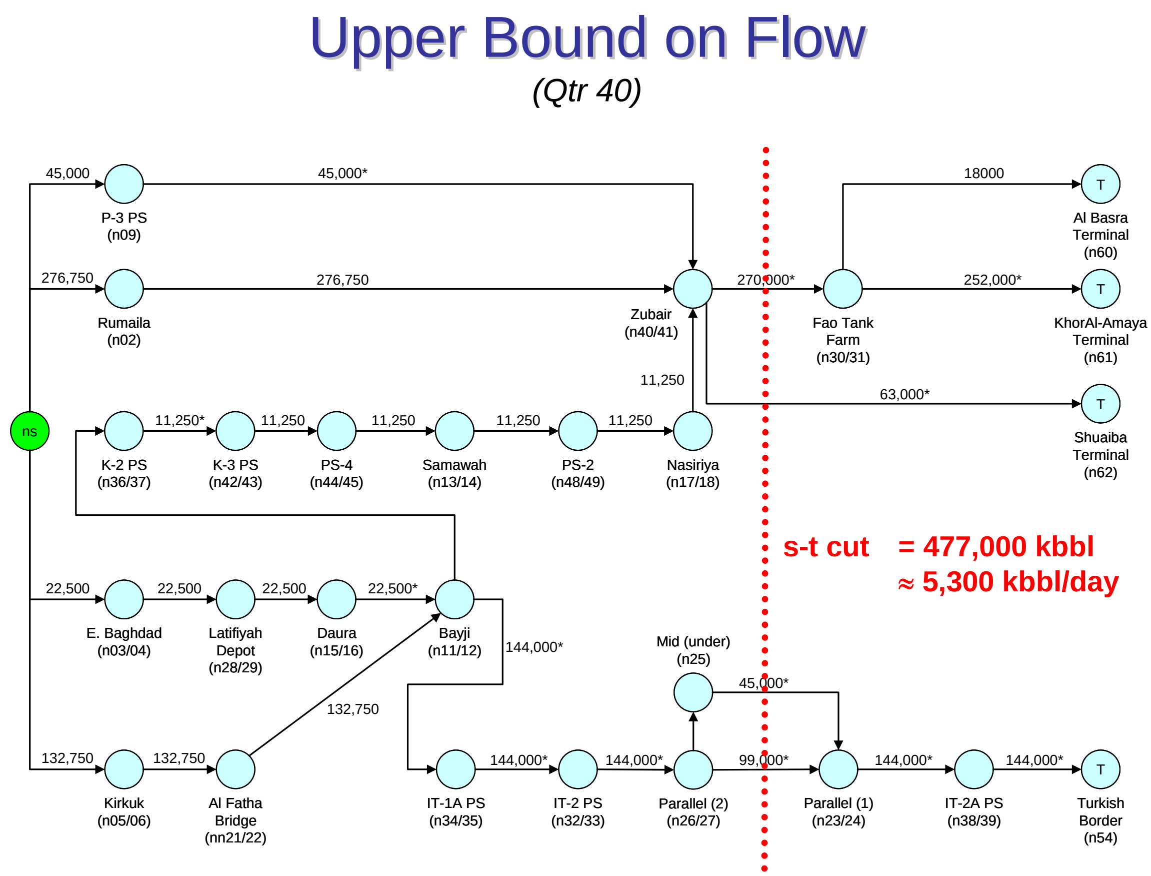


Figure 9. **Illustration of the Limiting Effects of Not Allowing New Construction and Redundancy**. This network diagram demonstrates the value of adding additional capacity and redundancy to the distribution network. Shown above are all the major pipelines and junctions, and their flow capacities (kbbl per quarter), at the end of the 40-quarter planning horizon if we do not allow for new construction. This network has a maximum capacity of 5,300 kbbd which is 2,425 kbbd below that of the Baseline scenario. Additionally, this network is completely interdictable by focusing attacks on the junctions at Zubair and Parallel (2) or upon the four pipelines indicated by the dashed line.

V. LESSONS LEARNED, RECOMMENDATIONS AND FUTURE WORK

A. REFLECTIONS ON GAMS AND THE TRI-LEVEL MODEL

Iraq's oil sector is unique from an infrastructure perspective and it lends itself to the application of the tri-level model. Unlike many regions of the world, Iraq has both a need and motivation to massively improve and expand its infrastructure over a reasonably long planning horizon. At the same time it must balance the need for added expansion with defensive measures to offset the anticipated moves of its enemies. In each of our five scenarios, Iraq's oil industry can increase production over the next ten years to more than the 3 million barrels per day objective established at the end of Operation Iraqi Freedom. Each scenario demonstrates a different mixture of capacity expansion and defenses to withstand a sustained insurgent campaign. The fraction of total expenditures devoted to defense is surprisingly stable in these cases: about 12%.

Defenses are critical, and the way we defend is equally important. Our key assumption when estimating defensive effectiveness (d_{ij}) for a pipeline is that we simply cannot hope to stop a determined attack. There are too many lines over too much distance to defend. However, oil pipelines can be built that are much harder to attack. The Baku-Tbilisi-Ceyhan pipeline is the longest in the world and it traverses some of the most politically unstable areas of that region. To decrease vulnerability to attack, engineers have buried its entire length. This dramatically increases the time and difficulty of mounting an attack, and thus gives the defender added opportunity to detect and defeat such attacks.

Iraq could bury its oil pipelines at an increased cost of 50-60%. Cathodic protection would increase this cost by about another 14%. We conjecture that such measures might dramatically reduce defense costs and increase their overall defense effectiveness.

B. ADDITIONAL RESEARCH TO BE ACCOMPLISHED

Iraq’s oil industry can withstand a sizeable sustained insurgency targeting its oil infrastructure if they follow through with some type of capital expansion and defense plan. We provide a general outline of how this might occur. However, additional work needs to be done determining what realistic construction and defense costs are and validating the quality of the estimation techniques. This will prove useful in establishing solid upper and lower bounds on the objective function of the model. Additionally, the values used for the v_{ij} and d_{ij} are notional. Simulation may prove useful in determining better values for these, though historical data from rapid pipeline repair teams and Baku-Tbilisi-Ceyhan pipeline is likely to be available in the near future. We may want to consider more than three different damage functions (those against normal pipelines, those against pump stations and control valves and those against the terminals located in the Persian Gulf) to account for different levels of attack. For example, we might consider allowing attackers 1-2 large attacks that inflict greater damage than any others.

APPENDIX A. SUMMARY OF GAMS ID'S, COMMON NAMES AND GEOGRAPHIC LOCATIONS

We assign each junction (node) in the Iraqi oil distribution network an identifier (used in GAMS), a common name, and a location in degrees of Latitude and Longitude. We employ an activity-on-arc model: the analogy between a length of oil pipe and an arc is obvious. But we also represent point-locations such as tank farms, pumping stations, and control valves as arcs. Any common name ending with (A) has a corresponding location with the same name ending in (B). Together the two locations produce an entry and exit node connected by a capacitated arc representing the volume of crude pumped per day. For example, East Baghdad field (A) and East Baghdad Field (B) represent the entry and exit points to the same location (sharing the same latitude and longitude).

Gams ID	**Node Common Name**	Lat	Long
ns	Global Source	--	--
n02	Rumaila	30.5333	47.4500
n03	East Baghdad field (A)	33.1148	44.5724
n04	East Baghdad field (B)	33.1148	44.5724
n05	Kirkuk (A)	35.4667	44.3920
n06	Kirkuk (B)	35.4667	44.3920
n07	Jambur	35.1608	44.5254
n08	Bai-Hassan	35.5992	44.2595
n09	P-3 pump station at field	32.0501	47.3103
n10	Khanaqin	34.4927	45.4172
n11	Bayji (A)	34.9729	43.6023
n12	Bayji (B)	34.9729	43.6023
n13	Samawah (A)	31.3000	45.2833
n14	Samawah (B)	31.3000	45.2833
n15	Daura (A)	33.0939	44.3064
n16	Daura (B)	33.0939	44.3064
n17	Nasiriya(A)	31.0333	46.2667
n18	Nasiriya(B)	31.0333	46.2667
n19	Naft Khaneh (A)	34.1795	45.4641
n20	Naft Khaneh (B)	34.1795	45.4641
n21	Al Fatha Bridge (A)	35.0564	43.6336
n22	Al Fatha Bridge (B)	35.0564	43.6336
n23	parallel section Surf/sub (1A)	36.2500	42.7500
n24	parallel section Surf/sub (1B)	36.2500	42.7500
n25	Parallel Mid Section (under)	36.1500	43.0000
n26	parallel section sub/Surf (2A)	35.9667	42.8500
n27	parallel section sub/Surf (2B)	35.9667	42.8500

Gams ID	**Node Common Name**	Lat	Long
n28	Latifah Depot (A)	32.9896	44.4472
n29	Latifah Depot (B)	32.9896	44.4472
n30	Fao Tank Farm (A)	30.2547	48.1864
n31	Fao Tank Farm (B)	30.2547	48.1864
n32	IT-2 pump station (A)	36.0793	43.0860
n33	IT-2 pump station (B)	36.0793	43.0860
n34	IT-1A pump station (A)	35.0146	43.5398
n35	IT-1A pump station (B)	35.0146	43.5398
n36	K-2 Pump Station (A)	34.7432	43.3677
n37	K-2 Pump Station (B)	34.7432	43.3677
n38	IT-2A pump station (A)	36.9144	42.7419
n39	IT-2A pump station (B)	36.9144	42.7419
n40	Zubair-2 (Zb-2) pumping station (A)	30.2756	48.1551
n41	Zubair-2 (Zb-2) pumping station (B)	30.2756	48.1551
n42	K-3 pump station (Haditha) (A)	34.0752	42.5698
n43	K-3 pump station (Haditha) (B)	34.0752	42.5698
n44	PS-4 pump station (A)	33.0522	43.5554
n45	PS-4 pump station (B)	33.0522	43.5554
n46	PS-3 pump station (Karbala) (A)	31.7996	44.3690
n47	PS-3 pump station (Karbala) (B)	31.7996	44.3690
n48	PS-2 pump station (A)	31.1667	45.5000
n49	PS-2 pump station (B)	31.1667	45.5000
n50	IPSA-2 pump station (A)	29.6493	46.6063
n51	IPSA-2 pump station (B)	29.6493	46.6063
n52	IT-1 Pump Station(Israel Split) (A)	34.1378	41.4433
n53	IT-1 Pump Station(Israel Split) (B)	34.1378	41.4433
n54	Turkish Border Crossing	37.2484	42.5698
n55	Kuwait Crossing	30.1921	48.1239
n56	Saudi Arabia Border	29.2317	46.5124
n57	Syria Crossing	34.2839	40.9270
n58	Jordan Border Crossing	32.8643	39.1434
n59	Iran Crossing	30.9854	47.8422
n60	Al Basra (Al Bakra) terminal	30.0251	48.4211
n61	Khor al-Amaya terminal	30.0459	48.4211
n62	Shuaiba (Umm Qasar Terminal)	30.2338	47.5763
nt	Global Terminal	--	--

APPENDIX B. SUMMARY OF PIPELINES AND LENGTHS

Appendix B is a summary of all the pipelines and the junctions they connect. There are 71 physical pipeline segments possible in the Iraq oil distribution network not including any modeling artifices that connect global sources (ns) and global terminals (nt). The lengths of the pipelines are initially calculated in nautical miles using the Great Circle Distance formula and converted to both U.S. statute miles and U.S. standard feet for future reference in the cost estimating model.

Iraqi Oil Distribution Network

From	Common Name	To	Common Name	Waypoint 1 (in decimal degrees)		Waypoint 2 (in decimal degrees)		Distance between wp1 and wp2		
				Lat 1	*Long 1*	*Lat 2*	*Long 2*	*naut miles*	*miUS*	*feet (US)*
n02	Rumaila	n40	Zubair-2 (Zb-2) pu	30.5333	47.4500	30.2756	48.1551	40	46	240,788
n03	East Baghdad fie	n04	East Baghdad fiel	33.1148	44.5724	33.1148	44.5724	-	-	-
n04	East Baghdad fie	n28	Latifah Depot (A)	33.1148	44.5724	32.9896	44.4472	10	11	59,556
n04	East Baghdad fie	n40	Zubair-2 (Zb-2) pu	33.1148	44.5724	30.2756	48.1551	250	288	1,518,480
n05	Kirkuk (A)	n06	Kirkuk (B)	35.4667	44.3920	35.4667	44.3920	-	-	-
n06	Kirkuk (B)	n03	East Baghdad fiel	35.4667	44.3920	33.1148	44.5724	141	163	859,143
n06	Kirkuk (B)	n21	Al Fatha Bridge (A	35.4667	44.3920	35.0564	43.6336	45	51	270,815
n07	Jambur	n05	Kirkuk (A)	35.1608	44.5254	35.4667	44.3920	19	22	118,371
n08	Bai-Hassan	n05	Kirkuk (A)	35.5992	44.2595	35.4667	44.3920	10	12	62,279
n09	P-3 pump station	n40	Zubair-2 (Zb-2) pu	32.0501	47.3103	30.2756	48.1551	115	132	698,536
n10	Khanaqin	n19	Naft Khaneh (A)	34.4927	45.4172	34.1795	45.4641	19	22	115,052
n11	Bayji (A)	n12	Bayji (B)	34.9729	43.6023	34.9729	43.6023	-	-	-
n12	Bayji (B)	n15	Daura (A)	34.9729	43.6023	33.0939	44.3064	118	136	717,282
n12	Bayji (B)	n34	IT-1A pump statio	34.9729	43.6023	35.0146	43.5398	4	5	24,074
n12	Bayji (B)	n36	K-2 Pump Station	34.9729	43.6023	34.7432	43.3677	18	21	109,261
n13	Samawah (A)	n14	Samawah (B)	31.3000	45.2833	31.3000	45.2833	-	-	-
n14	Samawah (B)	n46	PS-3 pump station	31.3000	45.2833	31.7996	44.3690	56	64	337,429
n14	Samawah (B)	n48	PS-2 pump station	31.3000	45.2833	31.1667	45.5000	14	16	83,215
n15	Daura (A)	n16	Daura (B)	33.0939	44.3064	33.0939	44.3064	-	-	-
n16	Daura (B)	n11	Bayji (A)	33.0939	44.3064	34.9729	43.6023	118	136	717,282
n17	Nasiriya(A)	n18	Nasiriya(B)	31.0333	46.2667	31.0333	46.2667	-	-	-
n18	Nasiriya(B)	n40	Zubair-2 (Zb-2) pu	31.0333	46.2667	30.2756	48.1551	108	124	653,480
n18	Nasiriya(B)	n48	PS-2 pump station	31.0333	46.2667	31.1667	45.5000	40	46	244,228
n19	Naft Khaneh (A)	n20	Naft Khaneh (B)	34.1795	45.4641	34.1795	45.4641	-	-	-
n20	Naft Khaneh (B)	n03	East Baghdad fiel	34.1795	45.4641	33.1148	44.5724	78	90	473,174
n21	Al Fatha Bridge (	n22	Al Fatha Bridge (E	35.0564	43.6336	35.0564	43.6336	-	-	-
n22	Al Fatha Bridge (	n11	Bayji (A)	35.0564	43.6336	34.9729	43.6023	5	6	31,844
n23	parallel section S	n24	parallel section Su	36.2500	42.7500	36.2500	42.7500	0	0	0
n24	parallel section S	n38	IT-2A pump statio	36.2500	42.7500	36.9144	42.7419	40	46	242,229
n25	Parallel Mid Sect	n23	parallel section Su	36.1500	43.0000	36.2500	42.7500	14	16	82,087
n26	parallel section s	n27	parallel section su	35.9667	42.8500	35.9667	42.8500	-	-	-
n27	parallel section s	n23	parallel section Su	35.9667	42.8500	36.2500	42.7500	18	20	107,399
n27	parallel section s	n25	Parallel Mid Secti	35.9667	42.8500	36.1500	43.0000	13	15	80,125
n28	Latifah Depot (A)	n29	Latifah Depot (B)	32.9896	44.4472	32.9896	44.4472	0	0	0
n29	Latifah Depot (B)	n15	Daura (A)	32.9896	44.4472	33.0939	44.3064	9	11	57,423
n30	Fao Tank Farm (	n31	Fao Tank Farm (E	30.2547	48.1864	30.2547	48.1864	-	-	-
n31	Fao Tank Farm (	n55	Kuwait Crossing	30.2547	48.1864	30.1921	48.1239	5	6	30,141
n31	Fao Tank Farm (	n61	Khor al-Amaya te	30.2547	48.1864	30.0459	48.4211	17	20	106,154
n31	Fao Tank Farm (	n60	Al Basra (Al Bakra	30.2547	48.1864	30.0251	48.4211	18	21	111,722
n32	IT-2 pump station	n33	IT-2 pump station	36.0793	43.0860	36.0793	43.0860	-	-	-
n33	IT-2 pump station	n26	parallel section su	36.0793	43.0860	35.9667	42.8500	13	15	80,791

Iraqi Oil Distribution Network										
From	Common Name	To	Common Name	Waypoint 1 (in decimal degrees)		Waypoint 2 (in decimal degrees)		Distance between wp1 and wp2		
				Lat 1	*Long 1*	*Lat 2*	*Long 2*	*naut miles*	*miUS*	*feet (US)*
n34	IT-1A pump stati	n35	IT-1A pump statio	35.0146	43.5398	35.0146	43.5398	-	-	-
n35	IT-1A pump stati	n32	IT-2 pump station	35.0146	43.5398	36.0793	43.0860	68	78	410,830
n36	K-2 Pump Station	n37	K-2 Pump Station	34.7432	43.3677	34.7432	43.3677	-	-	-
n37	K-2 Pump Station	n42	K-3 pump station	34.7432	43.3677	34.0752	42.5698	56	65	341,906
n38	IT-2A pump stati	n39	IT-2A pump statio	36.9144	42.7419	36.9144	42.7419	-	-	-
n39	IT-2A pump stati	n54	Turkish Border Cr	36.9144	42.7419	37.2484	42.5698	22	25	131,652
n40	Zubair-2 (Zb-2) p	n41	Zubair-2 (Zb-2) pu	30.2756	48.1551	30.2756	48.1551	-	-	-
n41	Zubair-2 (Zb-2) p	n02	Rumaila	30.2756	48.1551	30.5333	47.4500	40	46	240,788
n41	Zubair-2 (Zb-2) p	n17	Nasiriya(A)	30.2756	48.1551	31.0333	46.2667	108	124	653,480
n41	Zubair-2 (Zb-2) p	n30	Fao Tank Farm (A	30.2756	48.1551	30.2547	48.1864	2	2	12,457
n41	Zubair-2 (Zb-2) p	n50	IPSA-2 pump stat	30.2756	48.1551	29.6493	46.6063	89	102	539,833
n41	Zubair-2 (Zb-2) p	n59	Iran Crossing	30.2756	48.1551	30.9854	47.8422	46	52	276,760
n41	Zubair-2 (Zb-2) p	n62	Shuaiba (Umm Q	30.2756	48.1551	30.2338	47.5763	30	35	182,906
n42	K-3 pump station	n43	K-3 pump station	34.0752	42.5698	34.0752	42.5698	-	-	-
n43	K-3 pump station	n44	PS-4 pump station	34.0752	42.5698	33.0522	43.5554	79	91	478,259
n43	K-3 pump station	n52	IT-1 Pump Station	34.0752	42.5698	34.1378	41.4433	56	65	340,808
n44	PS-4 pump static	n45	PS-4 pump station	33.0522	43.5554	33.0522	43.5554	0	0	0
n45	PS-4 pump static	n42	K-3 pump station	33.0522	43.5554	34.0752	42.5698	79	91	478,259
n45	PS-4 pump static	n46	PS-3 pump station	33.0522	43.5554	31.7996	44.3690	86	99	520,779
n46	PS-3 pump static	n47	PS-3 pump station	31.7996	44.3690	31.7996	44.3690	-	-	-
n47	PS-3 pump static	n13	Samawah (A)	31.7996	44.3690	31.3000	45.2833	56	64	337,429
n47	PS-3 pump static	n44	PS-4 pump station	31.7996	44.3690	33.0522	43.5554	86	99	520,779
n48	PS-2 pump static	n49	PS-2 pump station	31.1667	45.5000	31.1667	45.5000	-	-	-
n49	PS-2 pump static	n13	Samawah (A)	31.1667	45.5000	31.3000	45.2833	14	16	83,215
n49	PS-2 pump static	n17	Nasiriya(A)	31.1667	45.5000	31.0333	46.2667	40	46	244,228
n50	IPSA-2 pump sta	n51	IPSA-2 pump stat	29.6493	46.6063	29.6493	46.6063	-	-	-
n51	IPSA-2 pump sta	n56	Saudi Arabia Bord	29.6493	46.6063	29.2317	46.5124	26	29	155,134
n52	IT-1 Pump Statio	n53	IT-1 Pump Station	34.1378	41.4433	34.1378	41.4433	-	-	-
n53	IT-1 Pump Statio	n57	Syria Crossing	34.1378	41.4433	34.2839	40.9270	27	31	164,518
n53	IT-1 Pump Statio	n58	Jordan Border Cro	34.1378	41.4433	32.8643	39.1434	138	159	839,245

Notes:
1. The distance between two waypoints is calculated using the great circle formula.
2. Distance = acos(sin(lat1)*sin(lat2)+cos(lat1)*cos(lat2)*cos(lon1-lon2))
   where all latitudes and longitudes are expressed in radians
3. 1 Nautical mile = 1.852 km (for sea and air navigation) = 1.1508 miUS = 6076.1033 ftUS

APPENDIX C. COSTS, DURATIONS AND FACTORS

This summarizes all the relevant data fields we use to estimate cost and duration for each activity in the model. The specific columns shown are as follows:

From	The origin of flow (GAMS ID)
To	The destination of flow (GAMS ID)
Pipe size	Diameter of the pipe in inches. Used in calculating pipeline costs.
Max cap	The published or expected capacity in thousands of barrels of oil per day (kbbd). Applicable only to pipelines and not junctions. A capacity of 99,999 is a modeling artifice indicating that the specified arc segment is a junction and can handle any flows entering and exiting it.
Distance	Length of the pipeline measured in standard U.S. feet. Used in calculating pipeline costs. A length of "-" indicates that the particular segment is a junction and has zero length.
# P/S	The number of intermediate pump stations required for that specific length of pipeline. A value of 0 indicates either a junction or a pipeline segment not long enough to warrant an intermediate facility.
Cost of New	The cost of new construction is normalized for fiscal year 2007, and represents the full cost to build this pipeline segment.
Cost to Upgrade	50% of the new construction cost and applies to pre-existing pipelines with degraded capacities.
Estimated time to complete	Represents the normal construction durations [quarters] to complete either new construction or upgrades.
Estimated time to crash complete	Represents the accelerated construction durations [quarters] to complete either new construction or upgrades.
Pipe Size Factor	Unit-less term used in calculating construction and upgrade durations.

* New construction arcs are indicated with shading

From	To	Pipe Size	Max Cap (kbbl/day)	Dist (ftUS)	# P/S	Cost of new construction (CY$07M)	Cost to upgrade infrastructure (CY$07M)	Estimated time to complete (qtrs)	Estimated time to crash complete (qtrs)	notional cost of one p/s	Pipe Size Factor
n02	n40	48	5050	240,788	1	289.24	144.62	1.0	1.0	9.779	1.2
n03	n04	--	99999	-	0	-	-	-	-		-
n04	n28	18	500	59,556	0	15.91	7.95	1.0	1.0	0.883	1.0
n04	n40	32	700	1,518,480	3	743.11	371.56	5.0	3.0	1.519	1.1
n05	n06	--	99999	-	0	-	-	-	-		-
n06	n03	32	700	859,143	2	420.91	210.45	3.0	2.0	1.519	1.1
n06	n21	40	1600	270,815	1	169.08	84.54	1.0	1.0	3.425	1.2
n07	n05	8	50	118,371	0	13.08	6.54	1.0	1.0	0.248	1.0
n08	n05	16	250	62,279	0	14.68	7.34	1.0	1.0	0.883	1.0
n09	n40	48	1000	698,536	1	812.88	406.44	2.0	2.0	2.154	1.2
n10	n19	12	250	115,052	0	19.92	9.96	1.0	1.0	0.883	1.0
n11	n12	--	99999	-	0	-	-	-	-		-
n12	n15	12	250	717,282	2	125.96	62.98	3.0	2.0	0.883	1.0
n12	n34	40	1600	24,074	0	14.73	7.36	1.0	1.0	3.425	1.2
n12	n36	12	250	109,261	0	18.92	9.46	1.0	1.0	0.883	1.0
n13	n14	--	99999	-	0	-	-	-	-		-
n14	n46	18	700	337,429	1	91.65	45.82	2.0	1.0	1.519	1.0
n14	n48	18	700	83,215	0	22.23	11.11	1.0	1.0	1.519	1.0
n15	n16	--	99999	-	0	-	-	-	-		-
n16	n11	12	250	717,282	2	125.96	62.98	3.0	2.0	0.883	1.0
n17	n18	--	99999	-	0	-	-	-	-		-
n18	n40	18	700	653,480	1	176.07	88.03	2.0	1.0	1.519	1.0
n18	n48	18	700	244,228	1	66.75	33.38	1.0	1.0	1.519	1.0
n19	n20	--	99999	-	0	-	-	-	-		-
n20	n03	12	250	473,174	1	82.81	41.40	2.0	1.0	0.883	1.0
n21	n22	--	99999	-	0	-	-	-	-		-
n22	n11	40	1600	31,844	0	19.48	9.74	1.0	1.0	3.425	1.2
n23	n24	--	99999	0	0	-	-	-	-		-
n24	n38	40	1600	242,229	1	151.59	75.80	1.0	1.0	3.425	1.2
n25	n23	40	500	82,087	0	50.21	25.11	1.0	1.0	0.883	1.2
n26	n27	--	99999	-	0	-	-	-	-		-
n27	n23	40	1100	107,399	0	65.69	32.85	1.0	1.0	2.154	1.2
n27	n25	40	500	80,125	0	49.01	24.51	1.0	1.0	0.883	1.2
n28	n29	--	99999	0	0	-	-	-	-		-
n29	n15	12	500	57,423	0	9.94	4.97	1.0	1.0	0.883	1.0
n30	n31	--	99999	-	0	-	-	-	-		-
n31	n55	18	200	30,141	0	8.05	4.03	1.0	1.0	0.883	1.0
n31	n61	32	2800	106,154	0	51.63	25.82	1.0	1.0	5.331	1.1
n31	n60	32	1600	111,722	0	54.34	27.17	1.0	1.0	3.425	1.1
n32	n33	--	99999	-	0	-	-	-	-		-

From	To	Pipe Size	Max Cap (kbbl/day)	Dist (ftUS)	# P/S	Cost of new construction (CY$07M)	Cost to upgrade infrastructure (CY$07M)	Estimated time to complete (qtrs)	Estimated time to crash complete (qtrs)	notional cost of one p/s		Pipe Size Factor
n33	n26	40	1600	80,791	0	49.42	24.71	1.0	1.0	3.425		1.2
n34	n35	--	99999	-	0	-	-	-	-			-
n35	n32	40	1600	410,830	1	254.72	127.36	2.0	1.0	3.425		1.2
n36	n37	--	99999	-	0	-	-	-	-			-
n37	n42	18	250	341,906	1	92.21	46.11	2.0	1.0	0.883		1.0
n38	n39	--	99999	-	0	-	-	-	-			-
n39	n54	40	1600	131,652	0	80.53	40.26	1.0	1.0	3.425		1.2
n40	n41	--	99999	-	0	-	-	-	-			-
n41	n02	32	700	240,788	1	118.63	59.32	1.0	1.0	1.519		1.1
n41	n17	18	700	653,480	1	176.07	88.03	2.0	1.0	1.519		1.0
n41	n30	32	3000	12,457	0	6.06	3.03	1.0	1.0	5.966		1.1
n41	n50	48	1700	539,833	1	629.96	314.98	2.0	1.0	3.425		1.2
n41	n59	18	250	276,760	1	74.81	37.40	1.0	1.0	0.883		1.0
n41	n62	32	700	182,906	0	88.96	44.48	1.0	1.0	1.519		1.1
n42	n43	--	99999	-	0	-	-	-	-			-
n43	n44	18	700	478,259	1	129.27	64.63	2.0	1.0	1.519		1.0
n43	n52	18	500	340,808	1	91.92	45.96	2.0	1.0	0.883		1.0
n44	n45	--	99999	0	0	-	-	-	-			-
n45	n42	18	700	478,259	1	129.27	64.63	2.0	1.0	1.519		1.0
n45	n46	18	700	520,779	1	140.62	70.31	2.0	1.0	1.519		1.0
n46	n47	--	99999	-	0	-	-	-	-			-
n47	n13	18	700	337,429	1	91.65	45.82	2.0	1.0	1.519		1.0
n47	n44	18	700	520,779	1	140.62	70.31	2.0	1.0	1.519		1.0
n48	n49	--	99999	-	0	-	-	-	-			-
n49	n13	18	700	83,215	0	22.23	11.11	1.0	1.0	1.519		1.0
n49	n17	18	700	244,228	1	66.75	33.38	1.0	1.0	1.519		1.0
n50	n51	--	99999	-	0	-	-	-	-			-
n51	n56	48	1700	155,134	0	180.05	90.02	1.0	1.0	3.425		1.2
n52	n53	--	99999	-	0	-	-	-	-			-
n53	n57	18	250	164,518	0	43.94	21.97	1.0	1.0	0.883		1.0
n53	n58	18	250	839,245	2	225.94	112.97	3.0	2.0	0.883		1.0
Subtotal (AVE):		26.125				812.876	406.438	5.000	3.000	9.779	max:	
						0.000	0.000	0.000	0.000	0.248	min:	
						91.795	45.897	1.042	0.775	2.048	ave:	

Points of comparison:

Trans-Afghanistan	42	1000	5,491,200	12	3,119.90	(Est. $2.5B BY$98 -> $2.9B CY$07 using MILCON indices)
Alaska Pipeline	48	2000	4,224,000	12	22,004.93	(Actual $8.0B BY$1977 -> $22.6B CY$2007 using MILCON indices)
Baku-Tbilisi-Ceyha	42	1000	1,459,600	2	496.23	
	46	1000	803,600	2	459.53	
	42	1000	3,158,640	3	1,084.26	
	36	1000	350,960	1	103.69	
					3,751.49	(Est. $2.9B BY$2002, currently $3.6-4.0B CY$2005 --> $3.52B CY$07)

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX D. FINAL GAMS DATA FILE

This appendix represents the actual data we provide to the GAMS tri-level optimization model. Each column is described as follows:

GAMS ID (i)	The origin of flow. “ns” indicates generic global source.
GAMS ID (j)	The destination of flow. “nt” indicates a generic global terminal.
Node Common Name (i or j)	English description of that particular GAMS ID.
Old Capacity	Present-day capacity of the specified pipeline section. [kbbd)]
Added Capacity	Amount of flow to be added by initiating a candidate capital expansion project on this pipeline segment. [kbbd]
Earliest Start	The earliest quarter (q) in the total planning horizon that this project can be started. A value of 0 indicates it may be started any time. A value of 10 indicates it may not be considered as a candidate for expansion until quarter 10.
Latest Start	The latest quarter (q) in the total planning horizon that this project can be started. A value of 0 indicates it may be started any time. Any value here must be greater than or equal to the value indicated in the earliest start column.
Min Duration	The “crashed” project duration. [quarters]
Max Duration	The normal project duration. [quarters]
Total Build Cost	The estimated cost of the particular project. This value accounts for whether or not this project is a new construction or existing pipeline upgrade project. [CY$2007M)]
$v_{i,j}$	penalty cost ($0 \le v_{i,j} \le 1$) [if attacked, fraction of flow interdicted]
$d_{i,j}$	defense effectiveness ($0 \le d_{i,j} \le v_{i,j}$) [fraction of flow defended]
Defense Cost	Total cost per quarter to defend that particular pipeline segment. [CY$2007M]
Pipeline Length	Total length of the indicated pipeline segment. [U.S. statute miles]

* New construction arcs are indicated with shading

GAMS ID (i)	Node Common Name (i)	GAMS ID (j)	Node Common Name (j)	Old Capacity [kbbl/day]	Added Capacity [kbbl/day]	Earliest Start	Latest Start	Min Duration [qtrs]	Max Duration [qtrs]	Total Build Cost [$M]	vij	dij	Defense Cost [$M/qtr]	Pipeline Length [miUS]
ns	Global Source	n02	Rumaila	99999	0	0	0	0	0	0	0	0	0	0
ns	Global Source	n03	East Baghdad field (A)	99999	0	0	0	0	0	0	0	0	0	0
ns	Global Source	n05	Kirkuk (A)	99999	0	0	0	0	0	0	0	0	0	0
ns	Global Source	n07	Jambur	99999	0	0	0	0	0	0	0	0	0	0
ns	Global Source	n08	Bai-Hassan	99999	0	0	0	0	0	0	0	0	0	0
ns	Global Source	n09	P-3 pump station at field	99999	0	0	0	0	0	0	0	0	0	0
ns	Global Source	n10	Khanaqin	99999	0	0	0	0	0	0	0	0	0	0
n02	Rumaila	n40	Zubair-2 (Zb-2) pumping s	2525	2525	0	0	1	1	144.6186	0.056	0.022	0.456	45.61
n03	East Baghdad field (A)	n04	East Baghdad field (B)	99999	0	0	0	0	0	0	0.333	0.333	0.110	0.00
n04	East Baghdad field (B)	n28	Latifah Depot (A)	250	250	0	0	1	1	7.95406	0.056	0.022	0.113	11.28
n04	East Baghdad field (B)	n40	Zubair-2 (Zb-2) pumping s	0	700	0	0	3	5	743.112	0.056	0.022	2.876	287.60
n05	Kirkuk (A)	n06	Kirkuk (B)	99999	0	0	0	0	0	0	0.333	0.333	0.160	0.00
n06	Kirkuk (B)	n03	East Baghdad field (A)	0	700	0	0	2	3	420.906	0.056	0.022	1.627	162.72
n06	Kirkuk (B)	n21	Al Fatha Bridge (A)	800	800	0	0	1	1	84.53777	0.056	0.022	0.513	51.29
n07	Jambur	n05	Kirkuk (A)	25	25	0	0	1	1	6.539429	0.056	0.022	0.224	22.42
n08	Bai-Hassan	n05	Kirkuk (A)	125	125	0	0	1	1	7.342218	0.056	0.022	0.118	11.80
n09	P-3 pump station at field	n40	Zubair-2 (Zb-2) pumping s	500	500	0	0	2	2	406.4382	0.056	0.022	1.323	132.30
n10	Khanaqin	n19	Naft Khaneh (A)	125	125	0	0	1	1	9.959923	0.056	0.022	0.218	21.79
n11	Bayji (A)	n12	Bayji (B)	99999	0	0	0	0	0	0	0.333	0.333	0.190	0.00
n12	Bayji (B)	n15	Daura (A)	125	125	0	0	2	3	62.97795	0.056	0.022	1.359	135.86
n12	Bayji (B)	n34	IT-1A pump station (A)	800	800	0	0	1	1	7.362577	0.056	0.022	0.046	4.56
n12	Bayji (B)	n36	K-2 Pump Station (A)	125	125	0	0	1	1	9.4586	0.056	0.022	0.207	20.69
n13	Samawah (A)	n14	Samawah (B)	99999	0	0	0	0	0	0	0.333	0.333	0.050	0.00
n14	Samawah (B)	n46	PS-3 pump station (Karba	350	350	0	0	1	2	45.82483	0.056	0.022	0.639	63.91
n14	Samawah (B)	n48	PS-2 pump station (A)	350	350	0	0	1	1	11.11383	0.056	0.022	0.158	15.76
n15	Daura (A)	n16	Daura (B)	99999	0	0	0	0	0	0	0.333	0.333	0.040	0.00
n16	Daura (B)	n11	Bayji (A)	125	125	0	0	2	3	62.97795	0.056	0.022	1.359	135.86
n17	Nasiriya(A)	n18	Nasiriya(B)	99999	0	0	0	0	0	0	0.333	0.333	0.050	0.00
n18	Nasiriya(B)	n40	Zubair-2 (Zb-2) pumping s	350	350	0	0	1	2	88.03497	0.056	0.022	1.238	123.77
n18	Nasiriya(B)	n48	PS-2 pump station (A)	350	350	0	0	1	1	33.37735	0.056	0.022	0.463	46.26
n19	Naft Khaneh (A)	n20	Naft Khaneh (B)	99999	0	0	0	0	0	0	0.333	0.333	0.020	0.00
n20	Naft Khaneh (B)	n03	East Baghdad field (A)	125	125	0	0	1	2	41.40399	0.056	0.022	0.896	89.62
n21	Al Fatha Bridge (A)	n22	Al Fatha Bridge (B)	99999	0	0	0	0	0	0	0.333	0.333	0.160	0.00
n22	Al Fatha Bridge (B)	n11	Bayji (A)	800	800	0	0	1	1	9.738931	0.056	0.022	0.060	6.03
n23	parallel section Surf/sub (	n24	parallel section Surf/sub (	99999	0	0	0	0	0	0	0.333	0.333	0.160	0.00
n24	parallel section Surf/sub (	n38	IT-2A pump station (A)	800	800	0	0	1	1	75.79522	0.056	0.022	0.459	45.88
n25	Parallel Mid Section (unde	n23	parallel section Surf/sub (	250	250	0	0	1	1	25.10535	0.056	0.022	0.155	15.55
n26	parallel section sub/Surf (	n27	parallel section sub/Surf (	99999	0	0	0	0	0	0	0.333	0.333	0.160	0.00
n27	parallel section sub/Surf (	n23	parallel section Surf/sub (	550	550	0	0	1	1	32.84666	0.056	0.022	0.203	20.34
n27	parallel section sub/Surf (	n25	Parallel Mid Section (unde	250	250	0	0	1	1	24.50506	0.056	0.022	0.152	15.18
n28	Latifah Depot (A)	n29	Latifah Depot (B)	99999	0	0	0	0	0	0	0.333	0.333	0.040	0.00
n29	Latifah Depot (B)	n15	Daura (A)	250	250	0	0	1	1	4.971032	0.056	0.022	0.109	10.88
n30	Fao Tank Farm (A)	n31	Fao Tank Farm (B)	99999	0	0	0	0	0	0	0.333	0.333	0.300	0.00

GAMS ID (i)	Node Common Name (i)	GAMS ID (j)	Node Common Name (j)	Old Capacity [kbbl/day]	Added Capacity [kbbl/day]	Earliest Start	Latest Start	Min Duration [qtrs]	Max Duration [qtrs]	Total Build Cost [$M]	vij	dij	Defense Cost [$M/qtr]	Pipeline Length [miUS]
n31	Fao Tank Farm (B)	n55	Kuwait Crossing	0	200	0	0	1	1	8.051	0.056	0.022	0.057	5.71
n31	Fao Tank Farm (B)	n61	Khor al-Amaya terminal	1400	1400	0	0	1	1	25.81547	0.056	0.022	0.201	20.11
n31	Fao Tank Farm (B)	n60	Al Basra (Al Bakra) termir	800	800	0	0	1	1	27.16953	0.056	0.022	0.212	21.16
n32	IT-2 pump station (A)	n33	IT-2 pump station (B)	99999	0	0	0	0	0	0	0.333	0.333	0.160	0.00
n33	IT-2 pump station (B)	n26	parallel section sub/Surf (	800	800	0	0	1	1	24.70903	0.056	0.022	0.153	15.30
n34	IT-1A pump station (A)	n35	IT-1A pump station (B)	99999	0	0	0	0	0	0	0.333	0.333	0.160	0.00
n35	IT-1A pump station (B)	n32	IT-2 pump station (A)	800	800	0	0	1	2	127.3596	0.056	0.022	0.778	77.81
n36	K-2 Pump Station (A)	n37	K-2 Pump Station (B)	99999	0	0	0	0	0	0	0.333	0.333	0.010	0.00
n37	K-2 Pump Station (B)	n42	K-3 pump station (Haditha	125	125	0	0	1	2	46.10503	0.056	0.022	0.648	64.76
n38	IT-2A pump station (A)	n39	IT-2A pump station (B)	99999	0	0	0	0	0	0	0.333	0.333	0.160	0.00
n39	IT-2A pump station (B)	n54	Turkish Border Crossing	800	800	0	0	1	1	40.26393	0.056	0.022	0.249	24.94
n40	Zubair-2 (Zb-2) pumping s	n41	Zubair-2 (Zb-2) pumping s	99999	0	0	0	0	0	0	0.333	0.333	0.620	0.00
n41	Zubair-2 (Zb-2) pumping s	n02	Rumaila	350	350	0	0	1	1	59.31633	0.056	0.022	0.456	45.61
n41	Zubair-2 (Zb-2) pumping s	n17	Nasiriya(A)	350	350	0	0	1	2	88.03497	0.056	0.022	1.238	123.77
n41	Zubair-2 (Zb-2) pumping s	n30	Fao Tank Farm (A)	1500	1500	0	0	1	1	3.029521	0.056	0.022	0.024	2.36
n41	Zubair-2 (Zb-2) pumping s	n50	IPSA-2 pump station (A)	0	1700	0	0	1	2	629.957	0.056	0.022	1.022	102.25
n41	Zubair-2 (Zb-2) pumping s	n59	Iran Crossing	0	250	0	0	1	1	74.809	0.056	0.022	0.524	52.42
n41	Zubair-2 (Zb-2) pumping s	n62	Shuaiba (Umm Qasar Te	350	350	0	0	1	1	44.48067	0.056	0.022	0.346	34.64
n42	K-3 pump station (Haditha	n43	K-3 pump station (Haditha	99999	0	0	0	0	0	0	0.333	0.333	0.060	0.00
n43	K-3 pump station (Haditha	n44	PS-4 pump station (A)	350	350	0	0	1	2	64.63336	0.056	0.022	0.906	90.58
n43	K-3 pump station (Haditha	n52	IT-1 Pump Station(Israel s	0	500	0	0	1	2	91.917	0.056	0.022	0.646	64.55
n44	PS-4 pump station (A)	n45	PS-4 pump station (B)	99999	0	0	0	0	0	0	0.333	0.333	0.050	0.00
n45	PS-4 pump station (B)	n42	K-3 pump station (Haditha	350	350	0	0	1	2	64.63336	0.056	0.022	0.906	90.58
n45	PS-4 pump station (B)	n46	PS-3 pump station (Karba	350	350	0	0	1	2	70.31218	0.056	0.022	0.986	98.64
n46	PS-3 pump station (Karba	n47	PS-3 pump station (Karba	99999	0	0	0	0	0	0	0.333	0.333	0.050	0.00
n47	PS-3 pump station (Karba	n13	Samawah (A)	350	350	0	0	1	2	45.82483	0.056	0.022	0.639	63.91
n47	PS-3 pump station (Karba	n44	PS-4 pump station (A)	350	350	0	0	1	2	70.31218	0.056	0.022	0.986	98.64
n48	PS-2 pump station (A)	n49	PS-2 pump station (B)	99999	0	0	0	0	0	0	0.333	0.333	0.050	0.00
n49	PS-2 pump station (B)	n13	Samawah (A)	350	350	0	0	1	1	11.11383	0.056	0.022	0.158	15.76
n49	PS-2 pump station (B)	n17	Nasiriya(A)	350	350	0	0	1	1	33.37735	0.056	0.022	0.463	46.26
n50	IPSA-2 pump station (A)	n51	IPSA-2 pump station (B)	99999	0	0	0	0	0	0	0.333	0.333	0.170	0.00
n51	IPSA-2 pump station (B)	n56	Saudi Arabia Border	0	1700	0	0	1	1	180.049	0.056	0.022	0.294	29.38
n52	IT-1 Pump Station(Israel s	n53	IT-1 Pump Station(Israel s	99999	0	0	0	0	0	0	0.333	0.333	0.050	0.00
n53	IT-1 Pump Station(Israel s	n57	Syria Crossing	0	250	0	0	1	1	43.944	0.056	0.022	0.312	31.16
n53	IT-1 Pump Station(Israel s	n58	Jordan Border Crossing	0	250	0	0	2	3	225.938	0.056	0.022	1.590	158.96
n54	Turkish Border Crossing	nt	Global Terminal	99999	0	0	0	0	0	0	0	0	0	0
nt	Global Terminal	ns	Global Source	99999	0	0	0	0	0	0	0	0	0	0
n55	Kuwait Crossing	nt	Global Terminal	99999	0	0	0	0	0	0	0	0	0	0
n56	Saudi Arabia Border	nt	Global Terminal	99999	0	0	0	0	0	0	0	0	0	0
n57	Syria Crossing	nt	Global Terminal	99999	0	0	0	0	0	0	0	0	0	0
n58	Jordan Border Crossing	nt	Global Terminal	99999	0	0	0	0	0	0	0	0	0	0
n59	Iran Crossing	nt	Global Terminal	99999	0	0	0	0	0	0	0	0	0	0
n60	Al Basra (Al Bakra) termir	nt	Global Terminal	99999	0	0	0	0	0	0	0.666	0.666	0.160	0
n61	Khor al-Amaya terminal	nt	Global Terminal	99999	0	0	0	0	0	0	0.666	0.666	0.120	0
n62	Shuaiba (Umm Qasar Te	nt	Global Terminal	99999	0	0	0	0	0	0	0	0	0	0

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX E. DISTRIBUTION OF “BASELINE ATTACKS”

This appendix summarizes the distribution of attacks by quarter against all possible Iraqi pipeline segments (*ij*). Pipelines are identified by their GAMS ID’s (Appendix A). The arc total column indicates the sum total of attacks against a particular pipeline over the entire 40-quarter planning horizon and can not be larger than the parameter *epoch_attacks*. The attack total row indicates the total number of attacks carried out during the indicated quarter. This value cannot exceed the parameter *atks_by_q*. The grand total of either of these totals the number of attacks over the entire planning horizon and cannot exceed the parameter *mx_atks*.

The *Baseline* scenario has the following settings:

Setting	Baseline
epoch_q	2
epoch_attacks	5
atks_by_q	10
mx_atks	300
atks_by_n_by_q	5
Construction factor	1.0
Defense factor	1.0

	Planning Horizon Quarter																																								Arc
i j	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	Total
n02-n40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	0	4
n03-n04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2	0	0	0	0	0	0	0	0	0	5
n04-n28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	5
n04-n40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n05-n06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	5
n06-n03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n06-n21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	1	0	0	0	0	0	0	0	0	0	0	5
n07-n05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n08-n05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n09-n40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	5
n10-n19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n11-n12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	5
n12-n15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n12-n34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n12-n36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	5
n13-n14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	3	0	0	1	0	0	0	0	0	0	0	5
n14-n46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n14-n48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n15-n16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	3	0	0	0	0	0	5
n16-n11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3	0	5
n17-n18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	3	0	0	0	0	5
n18-n40	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n18-n48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	1	0	0	0	0	0	5
n19-n20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n20-n03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n21-n22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	2	0	0	0	0	0	5
n22-n11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	4
n23-n24	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n24-n38	0	0	0	0	0	0	0	0	0	0	0	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n25-n23	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n26-n27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	0	0	0	0	1	0	0	0	5
n27-n23	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	5
n27-n25	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	5
n28-n29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	5
n29-n15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	5
n30-n31	0	0	2	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n31-n55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n31-n60	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n31-n61	0	0	3	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
n32-n33	0	0	0	0	0	0	0	0	0	0	3	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n33-n26	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	5
n34-n35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	2	0	0	0	0	0	0	5
n35-n32	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n36-n37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	5
n37-n42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5

i j	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	Arc Total
	Planning Horizon Quarter																																								
n38-n39	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n39-n54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n40-n41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	5
n41-n02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n41-n17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	5
n41-n30	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	5
n41-n50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	5
n41-n59	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n41-n62	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n42-n43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	3	0	0	0	5
n43-n44	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n43-n52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n44-n45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	2	0	0	0	0	0	0	0	0	5
n45-n42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n45-n46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n46-n47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2	0	0	1	0	0	0	0	0	0	0	0	0	4
n47-n13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n47-n44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n48-n49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n49-n13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n49-n17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n50-n51	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	5
n51-n56	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
n52-n53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	4
n53-n57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
n53-n58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
n54-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n55-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n56-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n57-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n58-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n59-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n60-nt	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n61-nt	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n62-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Attack Total	0	10	10	0	0	4	0	0	7	0	10	10	10	9	10	10	10	9	9	10	10	10	10	10	9	0	9	10	10	10	9	9	10	9	8	10	9	2	10	0	292

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX F. DISTRIBUTION OF "BIG ATTACKS"

This appendix summarizes the distribution of attacks by quarter against all possible Iraqi pipeline segments (*ij*). All field descriptions are similar to those discussed in Appendix E.

The *Big Attacks* scenario has the following settings:

Setting	Big Attack
epoch_q	2
epoch_attacks	15
atks_by_q	15
mx_atks	500
atks_by_n_by_q	5
Construction factor	1.0
Defense factor	1.0

i j	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	Arc Total
	Planning Horizon Quarter																																								
n02-n40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	5	0	0	4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	15
n03-n04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
n04-n28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2
n04-n40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	3
n05-n06	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
n06-n03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n06-n21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	15
n07-n05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n08-n05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n09-n40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	5	0	3	0	1	0	0	0	0	3	0	2	0	0	0	15
n10-n19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n11-n12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	3	0	0	0	0	0	0	9
n12-n15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n12-n34	0	0	0	0	0	0	0	0	2	5	0	0	0	0	0	0	0	3	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	15
n12-n36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n13-n14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	3	0	3	9
n14-n46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n14-n48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n15-n16	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
n16-n11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n17-n18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n18-n40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n18-n48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n19-n20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n20-n03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n21-n22	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
n22-n11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	15
n23-n24	0	0	3	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
n24-n38	0	0	0	0	0	0	0	0	0	0	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	15
n25-n23	0	0	0	0	0	0	0	0	0	2	0	5	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	14
n26-n27	0	0	0	0	0	0	3	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	3	0	0	0	0	0	0	0	0	0	12
n27-n23	0	0	0	0	0	0	0	0	0	3	5	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	15
n27-n25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	15
n28-n29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
n29-n15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n30-n31	0	0	0	0	0	3	3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	15
n31-n55	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
n31-n60	0	0	4	2	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14
n31-n61	0	0	0	2	0	0	1	3	0	0	0	0	0	0	4	2	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	15
n32-n33	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3	0	12
n33-n26	0	0	0	0	0	0	0	0	0	0	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15
n34-n35	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
n35-n32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	15
n36-n37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n37-n42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	6

i j	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	Arc Total
	Planning Horizon Quarter																																								
n38-n39	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	6
n39-n54	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0	5	0	0	0	0	15
n40-n41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	3	0	0	0	0	3	0	0	0	0	2	0	3	0	0	0	0	0	0	0	0	0	0	15
n41-n02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n41-n17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n41-n30	0	0	0	0	0	0	0	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	15
n41-n50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	5	0	0	0	3	0	0	0	5	0	0	0	0	0	15
n41-n59	0	0	0	0	5	5	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15
n41-n62	0	0	0	0	0	0	5	0	0	5	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15
n42-n43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	3	0	0	0	0	11
n43-n44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n43-n52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	5	0	5	0	0	0	15
n44-n45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	3
n45-n42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2
n45-n46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n46-n47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	3
n47-n13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n47-n44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
n48-n49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
n49-n13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n49-n17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n50-n51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	0	2	0	1	3	0	0	3	0	3	0	0	0	0	0	0	15
n51-n56	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	4	0	0	0	5	0	1	0	0	0	0	0	0	0	15
n52-n53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	0	0	3	0	3	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	15
n53-n57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	1	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
n53-n58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n54-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n55-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n56-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n57-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n58-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n59-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n60-nt	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	4
n61-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	4
n62-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Grand Total	6	3	8	7	8	11	13	13	12	15	15	15	15	13	15	11	9	14	15	15	15	15	9	15	15	15	15	15	14	8	15	15	15	11	15	15	11	9	6	15	496

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX G. DISTRIBUTION OF "REALLY BIG ATTACKS"

This appendix summarizes the distribution of attacks by quarter against all possible Iraqi pipeline segments (*ij*). All field descriptions are similar to those discussed in Appendix E.

The *Really Big Attacks* scenario has the following settings:

Setting	Really Big Attack
epoch_q	2
epoch_attacks	50
atks_by_q	30
mx_atks	500
atks_by_n_by_q	5
Construction factor	1.0
Defense factor	1.0

i j	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	Arc Total
	Planning Horizon Quarter																																								
n02-n40	0	0	0	0	0	0	0	0	0	0	5	5	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	5	0	0	0	5	5	5	5	5	5	0	50
n03-n04	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	5
n04-n28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n04-n40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n05-n06	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	3	0	9
n06-n03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n06-n21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	3	0	5	0	0	0	0	13
n07-n05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n08-n05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n09-n40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n10-n19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n11-n12	3	0	0	0	0	0	0	0	0	0	3	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	15
n12-n15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n12-n34	0	0	0	0	0	0	0	5	4	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	5	5	0	0	0	0	5	0	5	0	5	0	0	0	0	39
n12-n36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n13-n14	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
n14-n46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n14-n48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n15-n16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2	0	0	3	0	8
n16-n11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n17-n18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2
n18-n40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n18-n48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n19-n20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n20-n03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n21-n22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
n22-n11	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	15
n23-n24	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	12
n24-n38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	2
n25-n23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n26-n27	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
n27-n23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n27-n25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n28-n29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
n29-n15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n30-n31	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	3	18
n31-n55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n31-n60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	1	0	3
n31-n61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	3	5	0	0	0	0	1	0	14
n32-n33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	9
n33-n26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n34-n35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n35-n32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
n36-n37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
n37-n42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

i j	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	Arc Total
	Planning Horizon Quarter																																								
n38-n39	0	0	0	3	3	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12
n39-n54	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	1	0	0	0	0	11
n40-n41	0	0	3	0	0	3	3	0	0	0	0	0	3	3	3	3	3	0	0	3	0	0	0	3	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	33
n41-n02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n41-n17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n41-n30	0	0	0	0	0	0	0	0	0	0	2	5	0	0	0	0	0	0	0	0	5	5	5	0	0	5	0	5	5	1	0	0	0	5	2	0	0	5	0	0	50
n41-n50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	4	5	5	5	0	3	5	5	0	0	5	42
n41-n59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n41-n62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n42-n43	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	3	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
n43-n44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n43-n52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n44-n45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n45-n42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n45-n46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n46-n47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n47-n13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n47-n44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n48-n49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2
n49-n13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n49-n17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n50-n51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	3	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	2	0	14
n51-n56	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	0	0	5	5	0	5	0	5	5	5	5	0	0	0	0	0	0	5	50
n52-n53	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	3	3	3	0	0	0	0	3	0	3	3	0	3	0	0	0	0	0	0	0	0	0	0	3	26
n53-n57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n53-n58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n54-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n55-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n56-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n57-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n58-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n59-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n60-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	3
n61-nt	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	6
n62-nt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ns-n10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Grand Total	4	0	6	6	6	6	6	10	4	9	13	15	9	6	9	11	9	12	12	9	25	15	13	9	13	18	11	10	13	28	16	15	15	24	16	30	13	15	19	19	499

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX H. QUARTERLY FLOW RESULTS

Flow Achieved under Tri-Level Model

qtr	Baseline	Big Attk	Really Big Attk	Constr Cost +	Def. Cost +
q01	238,500	238,500	238,500	238,500	238,500
q02	355,500	270,000	355,500	355,500	355,500
q03	207,000	355,500	355,500	373,500	355,500
q04	427,500	427,500	355,500	396,000	427,500
q05	427,500	427,500	405,000	427,500	427,500
q06	427,500	427,500	427,500	450,000	168,750
q07	499,500	499,500	427,500	450,000	499,500
q08	499,500	499,500	427,500	198,000	499,500
q09	499,500	499,500	427,500	450,000	499,500
q10	499,500	499,500	416,250	450,000	499,500
q11	499,500	499,500	414,000	450,000	499,500
q12	499,500	499,500	522,000	522,000	355,500
q13	607,500	499,500	522,000	522,000	652,500
q14	652,500	499,500	522,000	522,000	652,500
q15	643,500	652,500	666,000	666,000	652,500
q16	652,500	654,750	666,000	666,000	654,750
q17	607,500	654,750	666,000	666,000	654,750
q18	654,750	666,000	666,000	666,000	654,750
q19	695,250	666,000	675,000	666,000	675,000
q20	652,500	666,000	675,000	666,000	663,750
q21	650,250	666,000	675,000	697,500	551,250
q22	663,750	666,000	675,000	697,500	695,250
q23	663,750	666,000	675,000	697,500	684,000
q24	695,250	697,500	675,000	697,500	695,250
q25	695,250	697,500	675,000	675,000	695,250
q26	695,250	697,500	675,000	697,500	695,250
q27	695,250	697,500	675,000	553,500	695,250
q28	663,750	697,500	675,000	697,500	540,000
q29	695,250	697,500	675,000	697,500	695,250
q30	562,500	697,500	675,000	697,500	695,250
q31	695,250	697,500	675,000	675,000	695,250
q32	695,250	697,500	675,000	697,500	695,250
q33	695,250	697,500	675,000	697,500	663,750
q34	684,000	697,500	675,000	697,500	695,250
q35	695,250	697,500	675,000	697,500	393,750
q36	695,250	697,500	675,000	697,500	695,250
q37	695,250	697,500	675,000	697,500	695,250
q38	695,250	697,500	675,000	684,000	540,000
q39	684,000	697,500	567,000	697,500	695,250
q40	695,250	697,500	675,000	697,500	695,250
total (kbbl)	23,856,750	23,958,000	23,222,250	23,548,500	23,193,000
kbbd (ave)	6,627	6,655	6,451	6,541	6,443
Export Potential ($Million)	1,192,837.50	1,197,900.00	1,161,112.50	1,177,425.00	1,159,650.00

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX I. BASELINE BUILD SCHEDULE

CONSTRUCTION ACTIVITIES AND SPENDING SCHEDULE SHOWING FLOW CAPACITIES AND UNATTACKED FLOWS ON PROJECT ARCS, AND TOTAL EXPORTS... (iteration 1)

(only arcs being expanded are shown; a star denotes one with flow at legacy capacity)

qtr		fm	to	d	cost	legacy capacity	expanded capacity	unattacked flow	export flow
q01									
	start:	n31	n61	d01	25.82	126000.00		63000.00	
	start:	n39	n54	d01	40.26	72000.00		72000.00*	
	start:	n41	n30	d01	3.03	135000.00		135000.00*	
	start:	n41	n62	d01	44.48	31500.00		31500.00*	
	finish:	n31	n61		0.00	126000.00	252000.00	63000.00	
	finish:	n39	n54		0.00	72000.00	144000.00	72000.00*	
	finish:	n41	n30		0.00	135000.00	270000.00	135000.00*	
	finish:	n41	n62		0.00	31500.00	63000.00	31500.00*	
									238500.00
q02									
	start:	n02	n40	d01	144.62	227250.00		227250.00*	
	start:	n12	n36	d01	9.46	11250.00		11250.00*	
	finish:	n02	n40		0.00	227250.00	454500.00	227250.00*	
	finish:	n12	n36		0.00	11250.00	22500.00	11250.00*	
									355500.00
q03									
	start:	n27	n23	d01	32.85	49500.00		49500.00*	
	start:	n41	n59	d01	74.81	0.00		0.00*	
	start:	n49	n13	d01	11.11	31500.00		0.00	
	finish:	n27	n23		0.00	49500.00	99000.00	49500.00*	
	finish:	n41	n59		0.00	0.00	22500.00	0.00*	
	finish:	n49	n13		0.00	31500.00	63000.00	0.00	
									405000.00
q04									
	start:	n06	n21	d01	84.54	72000.00		60750.00	
	finish:	n06	n21		0.00	72000.00	144000.00	60750.00	
									427500.00
q05									
	start:	n25	n23	d01	25.11	22500.00		0.00	
	start:	n35	n32	d02	63.68	72000.00		72000.00*	
	finish:	n25	n23		0.00	22500.00	45000.00	0.00	
									427500.00
q06									
	start:	n12	n34	d01	7.36	72000.00		72000.00*	
	start:	n22	n11	d01	9.74	72000.00		60750.00	
	start:	n24	n38	d01	75.80	72000.00		72000.00*	
	start:	n27	n25	d01	24.51	22500.00		22500.00*	
	start:	n31	n60	d01	27.17	72000.00		18000.00	
	start:	n33	n26	d01	24.71	72000.00		72000.00*	
	finish:	n12	n34		0.00	72000.00	144000.00	72000.00*	
	finish:	n22	n11		0.00	72000.00	144000.00	60750.00	
	finish:	n24	n38		0.00	72000.00	144000.00	72000.00*	
	finish:	n27	n25		0.00	22500.00	45000.00	22500.00*	
	finish:	n31	n60		0.00	72000.00	144000.00	18000.00	
	finish:	n33	n26		0.00	72000.00	144000.00	72000.00*	
	finish:	n35	n32		63.68	72000.00	144000.00	72000.00*	
									427500.00
q09									
	start:	n51	n56	d01	180.05	0.00		0.00*	
	finish:	n51	n56		0.00	0.00	153000.00	0.00*	
									499500.00
q11									
	start:	n41	n50	d02	314.98	0.00		0.00*	
									499500.00

```
q12
    finish: n41 n50          314.98       0.00   153000.00        0.00*
                                                                          499500.00
q13
    start:  n53 n57 d01       43.94       0.00                    0.00*
    finish: n53 n57            0.00       0.00    22500.00        0.00*
                                                                          652500.00
q15
    start:  n53 n58 d03       75.31       0.00                    0.00*
                                                                          652500.00
q16
    start:  n43 n52 d02       45.96       0.00                    0.00*
    build:  n53 n58           75.31       0.00                    0.00*
                                                                          652500.00
q17
    start:  n09 n40 d02      203.22   45000.00                45000.00*
    finish: n43 n52           45.96       0.00    45000.00        0.00*
    finish: n53 n58           75.31       0.00    22500.00        0.00*
                                                                          652500.00
q18
    start:  n16 n11 d03       20.99   11250.00                11250.00*
    finish: n09 n40          203.22   45000.00    90000.00    45000.00*
                                                                          654750.00
q19
    start:  n41 n17 d01      105.64   31500.00                31500.00*
    build:  n16 n11           20.99   11250.00                11250.00*
    finish: n41 n17            0.00   31500.00    63000.00    31500.00*
                                                                          695250.00
q20
    finish: n16 n11           20.99   11250.00    22500.00    11250.00*
                                                                          695250.00
q24
    start:  n45 n42 d01       77.56   31500.00                31500.00*
    finish: n45 n42            0.00   31500.00    63000.00    31500.00*
                                                                          695250.00
q26
    start:  n49 n17 d01       33.38   31500.00                    0.00
    finish: n49 n17            0.00   31500.00    63000.00        0.00
                                                                          695250.00
q27
    start:  n04 n40 d04      185.78       0.00                    0.00*
                                                                          695250.00
q28
    start:  n06 n03 d02      252.54       0.00                    0.00*
    start:  n18 n48 d01       33.38   31500.00                31500.00*
    build:  n04 n40          185.78       0.00                    0.00*
    finish: n18 n48            0.00   31500.00    63000.00    31500.00*
                                                                          695250.00
q29
    build:  n04 n40          185.78       0.00                    0.00*
    finish: n06 n03          252.54       0.00    63000.00        0.00*
                                                                          695250.00
q30
    finish: n04 n40          185.78       0.00    63000.00        0.00*
                                                                          695250.00
q31
    start:  n08 n05 d01        7.34   11250.00                    0.00
    start:  n10 n19 d01        9.96   11250.00                11250.00*
    start:  n14 n48 d01       11.11   31500.00                    0.00
    finish: n08 n05            0.00   11250.00    22500.00        0.00
    finish: n10 n19            0.00   11250.00    22500.00    11250.00*
    finish: n14 n48            0.00   31500.00    63000.00        0.00
                                                                          695250.00
q32
    start:  n07 n05 d01        6.54    2250.00                 2250.00*
    start:  n29 n15 d01        4.97   22500.00                22500.00*
    finish: n07 n05            0.00    2250.00     4500.00     2250.00*
    finish: n29 n15            0.00   22500.00    45000.00    22500.00*
                                                                          695250.00
```

```
q33
    start:  n18 n40 d02        44.02    31500.00                    0.00
                                                                           695250.00
q34
    finish: n18 n40            44.02    31500.00    63000.00        0.00
                                                                           695250.00
q38
    start:  n04 n28 d01         7.95    22500.00                22500.00*
    start:  n31 n55 d01         8.05        0.00                    0.00*
    finish: n04 n28             0.00    22500.00    45000.00    22500.00*
    finish: n31 n55             0.00        0.00    18000.00        0.00*
                                                                           695250.00
```

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX J. BIG ATTACKS BUILD SCHEDULE

```
CONSTRUCTION  ACTIVITIES  AND  SPENDING  SCHEDULE  SHOWING  FLOW  CAPACITIES  AND  UNATTACKED
FLOWS ON PROJECT ARCS, AND TOTAL EXPORTS...  (iteration    1)

(only arcs being expanded are shown; a star denotes one with flow at legacy capacity)

qtr         fm  to  d            cost     legacy     expanded  unattacked      export
                                        capacity     capacity        flow        flow
q01
    start:  n31 n61 d01         25.82   126000.00               63000.00
    start:  n39 n54 d01         40.26    72000.00               72000.00*
    start:  n41 n30 d01          3.03   135000.00              135000.00*
    start:  n41 n62 d01         44.48    31500.00               31500.00*
    finish: n31 n61              0.00   126000.00   252000.00   63000.00
    finish: n39 n54              0.00    72000.00   144000.00   72000.00*
    finish: n41 n30              0.00   135000.00   270000.00  135000.00*
    finish: n41 n62              0.00    31500.00    63000.00   31500.00*
                                                                            238500.00
q02
    start:  n02 n40 d01        144.62   227250.00              227250.00*
    start:  n12 n36 d01          9.46    11250.00               11250.00*
    finish: n02 n40              0.00   227250.00   454500.00  227250.00*
    finish: n12 n36              0.00    11250.00    22500.00   11250.00*
                                                                            355500.00
q03
    start:  n27 n23 d01         32.85    49500.00               49500.00*
    start:  n41 n59 d01         74.81        0.00                   0.00*
    start:  n49 n13 d01         11.11    31500.00                   0.00
    finish: n27 n23              0.00    49500.00    99000.00   49500.00*
    finish: n41 n59              0.00        0.00    22500.00       0.00*
    finish: n49 n13              0.00    31500.00    63000.00       0.00
                                                                            405000.00
q04
    start:  n06 n21 d01         84.54    72000.00               60750.00
    finish: n06 n21              0.00    72000.00   144000.00   60750.00
                                                                            427500.00
q05
    start:  n25 n23 d01         25.11    22500.00                   0.00
    start:  n35 n32 d02         63.68    72000.00               72000.00*
    finish: n25 n23              0.00    22500.00    45000.00       0.00
                                                                            427500.00
q06
    start:  n12 n34 d01          7.36    72000.00               72000.00*
    start:  n22 n11 d01          9.74    72000.00               60750.00
    start:  n24 n38 d01         75.80    72000.00               72000.00*
    start:  n27 n25 d01         24.51    22500.00               22500.00*
    start:  n31 n60 d01         27.17    72000.00               18000.00
    start:  n33 n26 d01         24.71    72000.00               72000.00*
    finish: n12 n34              0.00    72000.00   144000.00   72000.00*
    finish: n22 n11              0.00    72000.00   144000.00   60750.00
    finish: n24 n38              0.00    72000.00   144000.00   72000.00*
    finish: n27 n25              0.00    22500.00    45000.00   22500.00*
    finish: n31 n60              0.00    72000.00   144000.00   18000.00
    finish: n33 n26              0.00    72000.00   144000.00   72000.00*
    finish: n35 n32             63.68    72000.00   144000.00   72000.00*
                                                                            427500.00
q09
    start:  n51 n56 d01        180.05        0.00                   0.00*
    finish: n51 n56              0.00        0.00   153000.00       0.00*
                                                                            499500.00
q11
    start:  n41 n50 d02        314.98        0.00                   0.00*
                                                                            499500.00
```

```
q12
    finish: n41 n50           314.98        0.00   153000.00        0.00*
                                                                           499500.00
q13
    start:  n53 n57 d01        43.94        0.00                    0.00*
    finish: n53 n57             0.00        0.00    22500.00        0.00*
                                                                           652500.00
q15
    start:  n53 n58 d03        75.31        0.00                    0.00*
                                                                           652500.00
q16
    start:  n43 n52 d02        45.96        0.00                    0.00*
    build:  n53 n58            75.31        0.00                    0.00*
                                                                           652500.00
q17
    start:  n09 n40 d02       203.22    45000.00                45000.00*
    finish: n43 n52            45.96        0.00    45000.00        0.00*
    finish: n53 n58            75.31        0.00    22500.00        0.00*
                                                                           652500.00
q18
    start:  n16 n11 d03        20.99    11250.00                11250.00*
    finish: n09 n40           203.22    45000.00    90000.00    45000.00*
                                                                           654750.00
q19
    start:  n41 n17 d01       105.64    31500.00                31500.00*
    build:  n16 n11            20.99    11250.00                11250.00*
    finish: n41 n17             0.00    31500.00    63000.00    31500.00*
                                                                           695250.00
q20
    finish: n16 n11            20.99    11250.00    22500.00    11250.00*
                                                                           695250.00
q24
    start:  n45 n42 d01        77.56    31500.00                31500.00*
    finish: n45 n42             0.00    31500.00    63000.00    31500.00*
                                                                           695250.00
q26
    start:  n49 n17 d01        33.38    31500.00                    0.00
    finish: n49 n17             0.00    31500.00    63000.00        0.00
                                                                           695250.00
q27
    start:  n04 n40 d04       185.78        0.00                    0.00*
                                                                           695250.00
q28
    start:  n06 n03 d02       252.54        0.00                    0.00*
    start:  n18 n48 d01        33.38    31500.00                31500.00*
    build:  n04 n40           185.78        0.00                    0.00*
    finish: n18 n48             0.00    31500.00    63000.00    31500.00*
                                                                           695250.00
q29
    build:  n04 n40           185.78        0.00                    0.00*
    finish: n06 n03           252.54        0.00    63000.00        0.00*
                                                                           695250.00
q30
    finish: n04 n40           185.78        0.00    63000.00        0.00*
                                                                           695250.00
q31
    start:  n08 n05 d01         7.34    11250.00                    0.00
    start:  n10 n19 d01         9.96    11250.00                11250.00*
    start:  n14 n48 d01        11.11    31500.00                    0.00
    finish: n08 n05             0.00    11250.00    22500.00        0.00
    finish: n10 n19             0.00    11250.00    22500.00    11250.00*
    finish: n14 n48             0.00    31500.00    63000.00        0.00
                                                                           695250.00
q32
    start:  n07 n05 d01         6.54     2250.00                 2250.00*
    start:  n29 n15 d01         4.97    22500.00                22500.00*
    finish: n07 n05             0.00     2250.00     4500.00     2250.00*
    finish: n29 n15             0.00    22500.00    45000.00    22500.00*
                                                                           695250.00
```

```
q33
    start:  n18 n40 d02        44.02    31500.00                    0.00
                                                                          695250.00
q34
    finish: n18 n40            44.02    31500.00    63000.00        0.00
                                                                          695250.00
q38
    start:  n04 n28 d01         7.95    22500.00                22500.00*
    start:  n31 n55 d01         8.05        0.00                    0.00*
    finish: n04 n28             0.00    22500.00    45000.00    22500.00*
    finish: n31 n55             0.00        0.00    18000.00        0.00*
                                                                          695250.00
```

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX K. REALLY BIG ATTACKS BUILD SCHEDULE

```
CONSTRUCTION  ACTIVITIES  AND  SPENDING  SCHEDULE  SHOWING  FLOW  CAPACITIES  AND  UNATTACKED
FLOWS ON PROJECT ARCS, AND TOTAL EXPORTS...  (iteration    1)

(only arcs being expanded are shown; a star denotes one with flow at legacy capacity)

qtr         fm  to  d            cost     legacy    expanded  unattacked      export
                                        capacity    capacity        flow        flow
q01
    start:  n31 n61 d01         25.82  126000.00               63000.00
    start:  n39 n54 d01         40.26   72000.00               72000.00*
    start:  n41 n30 d01          3.03  135000.00              135000.00*
    start:  n41 n62 d01         44.48   31500.00               31500.00*
    finish: n31 n61              0.00  126000.00   252000.00   63000.00
    finish: n39 n54              0.00   72000.00   144000.00   72000.00*
    finish: n41 n30              0.00  135000.00   270000.00  135000.00*
    finish: n41 n62              0.00   31500.00    63000.00   31500.00*
                                                                           238500.00
q02
    start:  n02 n40 d01        144.62  227250.00              227250.00*
    start:  n12 n36 d01          9.46   11250.00               11250.00*
    finish: n02 n40              0.00  227250.00   454500.00  227250.00*
    finish: n12 n36              0.00   11250.00    22500.00   11250.00*
                                                                           355500.00
q03
    start:  n27 n23 d01         32.85   49500.00               49500.00*
    start:  n41 n59 d01         74.81       0.00                   0.00*
    start:  n49 n13 d01         11.11   31500.00                   0.00
    finish: n27 n23              0.00   49500.00    99000.00   49500.00*
    finish: n41 n59              0.00       0.00    22500.00       0.00*
    finish: n49 n13              0.00   31500.00    63000.00       0.00
                                                                           405000.00
q04
    start:  n06 n21 d01         84.54   72000.00               60750.00
    finish: n06 n21              0.00   72000.00   144000.00   60750.00
                                                                           427500.00
q05
    start:  n25 n23 d01         25.11   22500.00                   0.00
    start:  n35 n32 d02         63.68   72000.00               72000.00*
    finish: n25 n23              0.00   22500.00    45000.00       0.00
                                                                           427500.00
q06
    start:  n12 n34 d01          7.36   72000.00               72000.00*
    start:  n22 n11 d01          9.74   72000.00               60750.00
    start:  n24 n38 d01         75.80   72000.00               72000.00*
    start:  n27 n25 d01         24.51   22500.00               22500.00*
    start:  n31 n60 d01         27.17   72000.00               18000.00
    start:  n33 n26 d01         24.71   72000.00               72000.00*
    finish: n12 n34              0.00   72000.00   144000.00   72000.00*
    finish: n22 n11              0.00   72000.00   144000.00   60750.00
    finish: n24 n38              0.00   72000.00   144000.00   72000.00*
    finish: n27 n25              0.00   22500.00    45000.00   22500.00*
    finish: n31 n60              0.00   72000.00   144000.00   18000.00
    finish: n33 n26              0.00   72000.00   144000.00   72000.00*
    finish: n35 n32             63.68   72000.00   144000.00   72000.00*
                                                                           427500.00
q09
    start:  n51 n56 d01        180.05       0.00                   0.00*
    finish: n51 n56              0.00       0.00   153000.00       0.00*
                                                                           499500.00
q11
    start:  n41 n50 d02        314.98       0.00                   0.00*
                                                                           499500.00
```

```
q12
    finish: n41 n50           314.98        0.00   153000.00        0.00*
                                                                          499500.00
q13
    start:  n53 n57 d01        43.94        0.00                    0.00*
    finish: n53 n57             0.00        0.00    22500.00        0.00*
                                                                          652500.00
q15
    start:  n53 n58 d03        75.31        0.00                    0.00*
                                                                          652500.00
q16
    start:  n43 n52 d02        45.96        0.00                    0.00*
    build:  n53 n58            75.31        0.00                    0.00*
                                                                          652500.00
q17
    start:  n09 n40 d02       203.22    45000.00                45000.00*
    finish: n43 n52            45.96        0.00    45000.00        0.00*
    finish: n53 n58            75.31        0.00    22500.00        0.00*
                                                                          652500.00
q18
    start:  n16 n11 d03        20.99    11250.00                11250.00*
    finish: n09 n40           203.22    45000.00    90000.00    45000.00*
                                                                          654750.00
q19
    start:  n41 n17 d01       105.64    31500.00                31500.00*
    build:  n16 n11            20.99    11250.00                11250.00*
    finish: n41 n17             0.00    31500.00    63000.00    31500.00*
                                                                          695250.00
q20
    finish: n16 n11            20.99    11250.00    22500.00    11250.00*
                                                                          695250.00
q24
    start:  n45 n42 d01        77.56    31500.00                31500.00*
    finish: n45 n42             0.00    31500.00    63000.00    31500.00*
                                                                          695250.00
q26
    start:  n49 n17 d01        33.38    31500.00                    0.00
    finish: n49 n17             0.00    31500.00    63000.00        0.00
                                                                          695250.00
q27
    start:  n04 n40 d04       185.78        0.00                    0.00*
                                                                          695250.00
q28
    start:  n06 n03 d02       252.54        0.00                    0.00*
    start:  n18 n48 d01        33.38    31500.00                31500.00*
    build:  n04 n40           185.78        0.00                    0.00*
    finish: n18 n48             0.00    31500.00    63000.00    31500.00*
                                                                          695250.00
q29
    build:  n04 n40           185.78        0.00                    0.00*
    finish: n06 n03           252.54        0.00    63000.00        0.00*
                                                                          695250.00
q30
    finish: n04 n40           185.78        0.00    63000.00        0.00*
                                                                          695250.00
q31
    start:  n08 n05 d01         7.34    11250.00                    0.00
    start:  n10 n19 d01         9.96    11250.00                11250.00*
    start:  n14 n48 d01        11.11    31500.00                    0.00
    finish: n08 n05             0.00    11250.00    22500.00        0.00
    finish: n10 n19             0.00    11250.00    22500.00    11250.00*
    finish: n14 n48             0.00    31500.00    63000.00        0.00
                                                                          695250.00
q32
    start:  n07 n05 d01         6.54     2250.00                 2250.00*
    start:  n29 n15 d01         4.97    22500.00                22500.00*
    finish: n07 n05             0.00     2250.00     4500.00     2250.00*
    finish: n29 n15             0.00    22500.00    45000.00    22500.00*
                                                                          695250.00
```

```
q33
    start:  n18 n40 d02        44.02    31500.00                    0.00
                                                                           695250.00
q34
    finish: n18 n40            44.02    31500.00    63000.00        0.00
                                                                           695250.00
q38
    start:  n04 n28 d01         7.95    22500.00                22500.00*
    start:  n31 n55 d01         8.05        0.00                    0.00*
    finish: n04 n28             0.00    22500.00    45000.00    22500.00*
    finish: n31 n55             0.00        0.00    18000.00        0.00*
                                                                           695250.00
```

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX L. CONSTRUCTION COST PLUS BUILD SCHEDULE

CONSTRUCTION ACTIVITIES AND SPENDING SCHEDULE SHOWING FLOW CAPACITIES AND UNATTACKED FLOWS ON PROJECT ARCS, AND TOTAL EXPORTS... (iteration 1)

(only arcs being expanded are shown; a star denotes one with flow at legacy capacity)

qtr		fm	to	d	cost	legacy capacity	expanded capacity	unattacked flow	export flow
q01									
	start:	n27	n23	d01	49.27	49500.00		49500.00*	
	start:	n35	n32	d02	95.52	72000.00		72000.00*	
	start:	n37	n42	d02	34.58	11250.00		11250.00*	
	start:	n41	n30	d01	4.54	135000.00		135000.00*	
	finish:	n27	n23		0.00	49500.00	99000.00	49500.00*	
	finish:	n41	n30		0.00	135000.00	270000.00	135000.00*	
									238500.00
q02									
	start:	n12	n34	d01	11.04	72000.00		72000.00*	
	start:	n31	n55	d01	12.08	0.00		0.00*	
	start:	n49	n13	d01	16.67	31500.00		0.00	
	finish:	n12	n34		0.00	72000.00	144000.00	72000.00*	
	finish:	n31	n55		0.00	0.00	18000.00	0.00*	
	finish:	n35	n32		95.52	72000.00	144000.00	72000.00*	
	finish:	n37	n42		34.58	11250.00	22500.00	11250.00*	
	finish:	n49	n13		0.00	31500.00	63000.00	0.00	
									301500.00
q03									
	start:	n06	n21	d01	126.81	72000.00		72000.00*	
	start:	n39	n54	d01	60.40	72000.00		72000.00*	
	finish:	n06	n21		0.00	72000.00	144000.00	72000.00*	
	finish:	n39	n54		0.00	72000.00	144000.00	72000.00*	
									319500.00
q04									
	start:	n12	n36	d01	14.19	11250.00		0.00	
	start:	n16	n11	d03	31.49	11250.00		11250.00*	
	start:	n22	n11	d01	14.61	72000.00		60750.00	
	start:	n24	n38	d01	113.69	72000.00		72000.00*	
	start:	n33	n26	d01	37.06	72000.00		72000.00*	
	finish:	n12	n36		0.00	11250.00	22500.00	0.00	
	finish:	n22	n11		0.00	72000.00	144000.00	60750.00	
	finish:	n24	n38		0.00	72000.00	144000.00	72000.00*	
	finish:	n33	n26		0.00	72000.00	144000.00	72000.00*	
									319500.00
q05									
	start:	n41	n59	d01	112.21	0.00		0.00*	
	start:	n41	n62	d01	66.72	31500.00		31500.00*	
	build:	n16	n11		31.49	11250.00		0.00	
	finish:	n41	n59		0.00	0.00	22500.00	0.00*	
	finish:	n41	n62		0.00	31500.00	63000.00	31500.00*	
									369000.00
q06									
	start:	n25	n23	d01	37.66	22500.00		22500.00*	
	start:	n27	n25	d01	36.76	22500.00		22500.00*	
	start:	n31	n60	d01	40.75	72000.00		72000.00*	
	start:	n53	n57	d01	65.92	0.00		0.00*	
	finish:	n16	n11		31.49	11250.00	22500.00	11250.00*	
	finish:	n25	n23		0.00	22500.00	45000.00	22500.00*	
	finish:	n27	n25		0.00	22500.00	45000.00	22500.00*	
	finish:	n31	n60		0.00	72000.00	144000.00	72000.00*	
	finish:	n53	n57		0.00	0.00	22500.00	0.00*	
									416250.00
q07									
	start:	n31	n61	d01	38.72	126000.00		126000.00*	
	finish:	n31	n61		0.00	126000.00	252000.00	126000.00*	
									438750.00

```
q08
    start:  n04 n28 d01        11.93    22500.00                22500.00*
    start:  n07 n05 d01         9.81     2250.00                 2250.00*
    start:  n29 n15 d01         7.46    22500.00                22500.00*
    start:  n51 n56 d01       270.07        0.00                    0.00*
    finish: n04 n28             0.00    22500.00    45000.00    22500.00*
    finish: n07 n05             0.00     2250.00     4500.00     2250.00*
    finish: n29 n15             0.00    22500.00    45000.00    22500.00*
    finish: n51 n56             0.00        0.00   153000.00        0.00*
                                                                           438750.00
q10
    start:  n43 n52 d01       165.45        0.00                    0.00*
    finish: n43 n52             0.00        0.00    45000.00        0.00*
                                                                           438750.00
q11
    start:  n02 n40 d01       216.93   227250.00               227250.00*
    start:  n53 n58 d02       203.34        0.00                    0.00*
    finish: n02 n40             0.00   227250.00   454500.00   227250.00*
                                                                           438750.00
q12
    finish: n53 n58           203.34        0.00    22500.00        0.00*
                                                                           522000.00
q13
    start:  n47 n44 d02        52.73    31500.00                22500.00
                                                                           544500.00
q14
    start:  n18 n40 d01       158.46    31500.00                    0.00
    finish: n18 n40             0.00    31500.00    63000.00        0.00
    finish: n47 n44            52.73    31500.00    63000.00    22500.00
                                                                           544500.00
q15
    start:  n14 n46 d01        82.48    31500.00                22500.00
    finish: n14 n46             0.00    31500.00    63000.00    22500.00
                                                                           544500.00
q18
    start:  n41 n50 d02       472.47        0.00                    0.00*
                                                                           544500.00
q19
    finish: n41 n50           472.47        0.00   153000.00        0.00*
                                                                           544500.00
q21
    start:  n09 n40 d02       304.83    45000.00                45000.00*
                                                                           666000.00
q22
    finish: n09 n40           304.83    45000.00    90000.00    45000.00*
                                                                           666000.00
q26
    start:  n18 n48 d01        50.07    31500.00                22500.00
    start:  n49 n17 d01        50.07    31500.00                    0.00
    finish: n18 n48             0.00    31500.00    63000.00    22500.00
    finish: n49 n17             0.00    31500.00    63000.00        0.00
                                                                           697500.00
q27
    start:  n04 n40 d03       445.87        0.00                    0.00*
                                                                           697500.00
q28
    build:  n04 n40           445.87        0.00                    0.00*
                                                                           697500.00
q29
    finish: n04 n40           445.87        0.00    63000.00        0.00*
                                                                           697500.00
q30
    start:  n20 n03 d01        74.53    11250.00                    0.00
    finish: n20 n03             0.00    11250.00    22500.00        0.00
                                                                           697500.00
q33
    start:  n12 n15 d02        56.68    11250.00                    0.00
    start:  n45 n42 d02        48.48    31500.00                22500.00
                                                                           697500.00
```

```
q34
    start:  n10 n19 d01        14.94    11250.00                11250.00*
    start:  n41 n02 d01        88.97    31500.00                    0.00
    start:  n47 n13 d02        34.37    31500.00                    0.00
    finish: n10 n19             0.00    11250.00    22500.00    11250.00*
    finish: n12 n15            56.68    11250.00    22500.00        0.00
    finish: n41 n02             0.00    31500.00    63000.00        0.00
    finish: n45 n42            48.48    31500.00    63000.00    22500.00
                                                                           697500.00
q35
    start:  n08 n05 d01        11.01    11250.00                    0.00
    start:  n14 n48 d01        16.67    31500.00                    0.00
    finish: n08 n05             0.00    11250.00    22500.00        0.00
    finish: n14 n48             0.00    31500.00    63000.00        0.00
    finish: n47 n13            34.37    31500.00    63000.00        0.00
                                                                           697500.00
q37
    start:  n43 n44 d01       116.34    31500.00                    0.00
    finish: n43 n44             0.00    31500.00    63000.00        0.00
                                                                           697500.00
q38
    start:  n41 n17 d01       158.46    31500.00                31500.00*
    finish: n41 n17             0.00    31500.00    63000.00    31500.00*
                                                                           697500.00
q39
    start:  n45 n46 d01       126.56    31500.00                    0.00
    finish: n45 n46             0.00    31500.00    63000.00        0.00
                                                                           697500.00
```

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX M. DEFENSE COST PLUS BUILD SCHEDULE

```
CONSTRUCTION  ACTIVITIES  AND  SPENDING  SCHEDULE  SHOWING  FLOW  CAPACITIES  AND  UNATTACKED
FLOWS ON PROJECT ARCS, AND TOTAL EXPORTS...  (iteration    1)

(only arcs being expanded are shown; a star denotes one with flow at legacy capacity)

qtr         fm  to  d           cost     legacy     expanded  unattacked      export
                                       capacity     capacity        flow        flow
q01
    start:  n04 n28 d01         7.95    22500.00                11250.00
    start:  n31 n55 d01         8.05        0.00                    0.00*
    start:  n41 n30 d01         3.03   135000.00               135000.00*
    start:  n41 n59 d01        74.81        0.00                    0.00*
    finish: n04 n28             0.00    22500.00     45000.00   11250.00
    finish: n31 n55             0.00        0.00     18000.00       0.00*
    finish: n41 n30             0.00   135000.00    270000.00  135000.00*
    finish: n41 n59             0.00        0.00     22500.00       0.00*
                                                                           238500.00
q02
    start:  n02 n40 d01       144.62   227250.00               227250.00*
    start:  n31 n60 d01        27.17    72000.00                72000.00*
    finish: n02 n40             0.00   227250.00    454500.00  227250.00*
    finish: n31 n60             0.00    72000.00    144000.00   72000.00*
                                                                           342000.00
q03
    start:  n12 n34 d01         7.36    72000.00                72000.00*
    start:  n35 n32 d02        63.68    72000.00                72000.00*
    start:  n41 n62 d01        44.48    31500.00                31500.00*
    finish: n12 n34             0.00    72000.00    144000.00   72000.00*
    finish: n41 n62             0.00    31500.00     63000.00   31500.00*
                                                                           396000.00
q04
    start:  n27 n23 d01        32.85    49500.00                49500.00*
    start:  n53 n57 d01        43.94        0.00                    0.00*
    finish: n27 n23             0.00    49500.00     99000.00   49500.00*
    finish: n35 n32            63.68    72000.00    144000.00   72000.00*
    finish: n53 n57             0.00        0.00     22500.00       0.00*
                                                                           427500.00
q05
    start:  n43 n52 d01       110.30        0.00                    0.00*
    finish: n43 n52             0.00        0.00     45000.00       0.00*
                                                                           427500.00
q06
    start:  n27 n25 d01        24.51    22500.00                    0.00
    finish: n27 n25             0.00    22500.00     45000.00       0.00
                                                                           450000.00
q07
    start:  n22 n11 d01         9.74    72000.00                72000.00*
    start:  n37 n42 d01        55.33    11250.00                11250.00*
    finish: n22 n11             0.00    72000.00    144000.00   72000.00*
    finish: n37 n42             0.00    11250.00     22500.00   11250.00*
                                                                           450000.00
q08
    start:  n06 n21 d01        84.54    72000.00                72000.00*
    finish: n06 n21             0.00    72000.00    144000.00   72000.00*
                                                                           450000.00
q09
    start:  n33 n26 d01        24.71    72000.00                72000.00*
    finish: n33 n26             0.00    72000.00    144000.00   72000.00*
                                                                           450000.00
```

```
q10
    start:  n24 n38 d01        75.80    72000.00                72000.00*
    start:  n25 n23 d01        25.11    22500.00                22500.00*
    start:  n39 n54 d01        40.26    72000.00                72000.00*
    finish: n24 n38             0.00    72000.00   144000.00    72000.00*
    finish: n25 n23             0.00    22500.00    45000.00    22500.00*
    finish: n39 n54             0.00    72000.00   144000.00    72000.00*
                                                                          450000.00
q11
    start:  n45 n46 d02        35.16    31500.00                    0.00
                                                                          522000.00
q12
    finish: n45 n46            35.16    31500.00    63000.00        0.00
                                                                          522000.00
q13
    start:  n41 n50 d02       314.98        0.00                    0.00*
    start:  n51 n56 d01       180.05        0.00                    0.00*
    finish: n51 n56             0.00        0.00   153000.00        0.00*
                                                                          522000.00
q14
    finish: n41 n50           314.98        0.00   153000.00        0.00*
                                                                          522000.00
q15
    start:  n16 n11 d02        37.79    11250.00                11250.00*
                                                                          654750.00
q16
    start:  n12 n36 d01         9.46    11250.00                11250.00*
    finish: n12 n36             0.00    11250.00    22500.00    11250.00*
    finish: n16 n11            37.79    11250.00    22500.00    11250.00*
                                                                          654750.00
q17
    start:  n09 n40 d02       203.22    45000.00                45000.00*
                                                                          666000.00
q18
    finish: n09 n40           203.22    45000.00    90000.00    45000.00*
                                                                          666000.00
q20
    start:  n14 n46 d02        22.91    31500.00                    0.00
                                                                          675000.00
q21
    start:  n31 n61 d01        25.82   126000.00               126000.00*
    start:  n41 n17 d02        44.02    31500.00                    0.00
    start:  n45 n42 d02        32.32    31500.00                    0.00
    start:  n47 n44 d02        35.16    31500.00                    0.00
    start:  n49 n13 d01        11.11    31500.00                    0.00
    finish: n14 n46            22.91    31500.00    63000.00        0.00
    finish: n31 n61             0.00   126000.00   252000.00   126000.00*
    finish: n49 n13             0.00    31500.00    63000.00        0.00
                                                                          675000.00
q22
    start:  n18 n48 d01        33.38    31500.00                    0.00
    finish: n18 n48             0.00    31500.00    63000.00        0.00
    finish: n41 n17            44.02    31500.00    63000.00        0.00
    finish: n45 n42            32.32    31500.00    63000.00        0.00
    finish: n47 n44            35.16    31500.00    63000.00        0.00
                                                                          675000.00
q28
    start:  n53 n58 d02       135.56        0.00                    0.00*
                                                                          675000.00
q29
    start:  n41 n02 d01        59.32    31500.00                    0.00
    finish: n41 n02             0.00    31500.00    63000.00        0.00
    finish: n53 n58           135.56        0.00    22500.00        0.00*
                                                                          675000.00
q30
    start:  n04 n40 d03       297.24        0.00                    0.00*
    start:  n10 n19 d01         9.96    11250.00                11250.00*
    finish: n10 n19             0.00    11250.00    22500.00    11250.00*
                                                                          697500.00
```

```
q31
    build:  n04 n40           297.24         0.00                        0.00*
                                                                                  697500.00
q32
    start:  n06 n03 d02       252.54         0.00                        0.00*
    finish: n04 n40           297.24         0.00     63000.00           0.00*
                                                                                  697500.00
q33
    finish: n06 n03           252.54         0.00     63000.00           0.00*
                                                                                  697500.00
q34
    start:  n47 n13 d01        54.99     31500.00                        0.00
    finish: n47 n13             0.00     31500.00     63000.00           0.00
                                                                                  697500.00
q37
    start:  n07 n05 d01         6.54      2250.00                        0.00
    start:  n08 n05 d01         7.34     11250.00                    11250.00*
    finish: n07 n05             0.00      2250.00      4500.00           0.00
    finish: n08 n05             0.00     11250.00     22500.00       11250.00*
                                                                                  697500.00
q39
    start:  n18 n40 d01       105.64     31500.00                        0.00
    start:  n20 n03 d01        49.68     11250.00                        0.00
    start:  n43 n44 d01        77.56     31500.00                        0.00
    finish: n18 n40             0.00     31500.00     63000.00           0.00
    finish: n20 n03             0.00     11250.00     22500.00           0.00
    finish: n43 n44             0.00     31500.00     63000.00           0.00
                                                                                  697500.00
```

THIS PAGE INTENTIONALLY LEFT BLANK

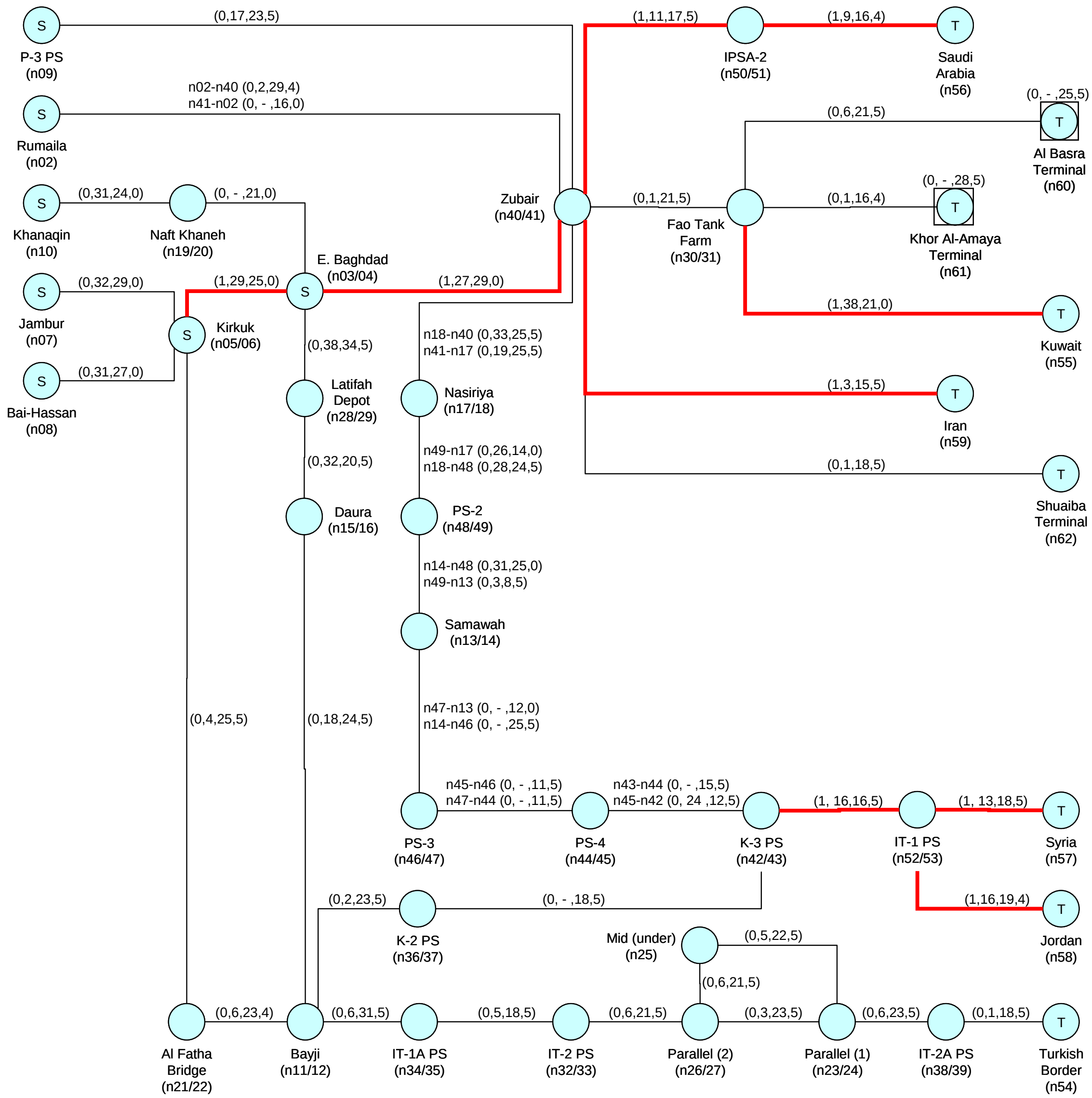
APPENDIX N. BIRD'S EYE OF "BASELINE ATTACKS"

This diagram provides a condensed view of the *Baseline* Iraqi oil distribution network over the 40-quarter planning horizon. Junctions are represented by circles and the pipelines by solid lines. Each junction is identified by its common name and the applicable GAMS ID's. Junctions annotated with an "S" indicate they are sources of crude oil, and junctions with a "T" indicate the terminals. Al Basra and Khor Al-Amaya terminals are also surrounded by a box to indicate that they are offshore oil facilities and subject to insurgent attacks. Each pipeline has a set of four numbers inside parentheses. These values indicate the following:

(X, - , - , -)	'0' indicates the pipeline is pre-existing. '1' indicates the pipeline is new construction.
(- ,X, - , -)	Indicates the quarter in which the pipeline is either upgraded or new construction begins. A value of '-' indicates no capital expansion project is initiated during the planning horizon.
(- , - ,X, -)	Indicates the number of quarters this particular pipeline is defended during the planning horizon.
(- , - , - ,X)	Indicates the number of times the pipeline is attacked. This value can not exceed *epoch_attacks*.

Baseline Scenario

“Bird’s Eye View”



ij	Common Name	Total Flow (kbbl)	ij	Common Name	Total Flow (kbbl)
n54-nt	Turkish Border Crossing	5,060,250	n59-nt	Iran Crossing	810,000
n55-nt	Kuwait Crossing	-	n60-nt	Al Basra (Al Bakra) terminal	3,402,000
n56-nt	Saudi Arabia Border	4,257,000	n61-nt	Khor al-Amaya terminal	7,065,000
n57-nt	Syria Crossing	425,250	n62-nt	Shuaiba (Umm Qasar Terminal)	2,439,000
n58-nt	Jordan Border Crossing	398,250			
			Grand Total		23,856,750

LIST OF REFERENCES

Alexander, 2005a, "Iraq's Oil and Power Infrastructure Attacked 196 Times Since War", Alexander's Gas and Oil Connections: News and Trends, Middle East, 10(3). Retrieved from http://www.gasandoil.com/goc/news/ntm50659.htm on 1 March 2005. 10 February.

Alexander, 2005b, "Iraq Oil Exports Officially Resume to Turkey", Alexander's Gas and Oil Connections: News and Trends, Middle East, 10(9). Retrieved from http://www.gasandoil.com/goc/news/ntm51976.htm on 31 May 2005. 19 April.

Alexander, 2005c, "Iraq's Oil Exports from Southern Offshore Terminals Expected to Fall", Alexander's Gas and Oil Connections: News and Trends, Middle East, 10(9). Retrieved from http://www.gasandoil.com/goc/news/ntm52132.htm on 31 May 2005. 25 April.

Alexander, 2005d, "Iraqi Oil Output Seen Below Capacity Again in 2005", Alexander's Gas and Oil Connections: News and Trends, Middle East, 10(4). Retrieved from http://www.gasandoil.com/goc/news/ntm50866.htm on 1 March 2005. 2 August.

Aljazeera, 2003, "Iraq-Saudi Oil Pipeline Unusable", Aljazeera.Net online news service. Retrieved from http://english.aljazeera.net/NR/exeres/C42E2CC2-92AA-4D31-A338-C9B733F11649.htm on 20 August 2005. 20 October.

Alyeska, 2003, "Pipeline Facts", Alyeska Pipeline Service Company. Retrieved from http://www.alyeska-pipe.com/PipelineFacts/pipelineconstruction.html on 25 July 2005.

Barazanji, Yayha, 2004, "Iraqi Oil Infrastructure Losing Billions", Yahoo! News as published online at Energy Bulletin (http://www.energybulletin.net/). Retrieved from http://www.energybulletin.net/3422.html on 5 July 2005. 30 November.

Boyle Engineering Corporation, 2002, "Chapter 4 - Design Criteria and Cost Estimating Methodology", *The Final Draft of the Regional Colorado River Conveyance Feasibility Study prepared for the San Diego County Water Authority*. 18 pages.
Provided electronically by Lori Floyd, PMA Consultants, LLC, on 18 July 2005 and available online at
http://sdcwa.org/news/pdf/Binational/Boyle2002/04designcriteria_costmethodology.pdf, 20 February.

Brown, G., Carlyle, M., Harney, R., Skroch, E., and K. Wood, 2005a, "Interdicting a Nuclear Weapons Project" (in review).

Brown, G., Carlyle, M., Salmeron, J. and K. Wood, 2005b, "Defending Critical Infrastructure" (in review).

Brown, G., Dell, R., and Wood, K., 1997, "Optimization and Persistence," Interfaces, 27, pp. 15-37.

Brown, G. and A. Washburn, 2000 "The Fast Theater Model (FATHM)", NPS-OR-01-002-PR, Naval Postgraduate School, Monterey, CA, October (revised January 2005), 32 pages.

Bryce, Robert, 2004, "America's Achilles' Heel", Salon.Com. Retrieved from http://www.salon.com/opinion/feature/2004/08/16/iraq_oil/print.html on 18 July 2005. 16 August.

Central Intelligence Agency, 2005, "CIA World Factbook", Discussion and analysis on the country of Iraq. Retrieved from http://www.cia.gov/cia/publications/factbook/geos/iz.html on 14 August 2005. 9 August.

Clark, Maureen 2001: "Oil Spilling from Alaska Pipeline", Associated Press as published online at climateark.org. Retrieved from http://www.climateark.org/articles/2001/3rd/oilsfrom.htm on 18 July 2005. 6 October.

Dalal, Khalid, 2004, "Feasibility Study on Jordan-Iraq Oil Pipeline to Be Conducted", Jordan Times as published online at jordanembassyus.org. Retrieved from http://www.jordanembassyus.org/10132004002.htm on 20 august 2005. 13 October.

Dauenhauer, Katrin, 2003, "Washington Lends Muscle to Besieged Columbian Pipeline", Inter Press Service as published online at Common Dreams News Center. Retrieved from http://www.commondreams.org/headlines03/0701-09.htm on 18 July 2005. 1 July.

Defense Modeling and Simulation Office (DMSO), 2005, DIAMOND-US 2.3 using DROMAS 3.03. Software not available for public release.

Devore, Jay L., 2004, *Probability and Statistics for Engineering and the Sciences* (6th ed.), Belmont: Brooks/Cole.

Feld, Lowell, 2005a, "Iraq Country Analysis Brief" Energy Information Administration, Country Analysis Briefs - Iraq. Retrieved from http://www.eia.doe.gov/emeu/cabs/iraq.html on 10 June 2005. June.

Feld, Lowell, 2005b, "Iraq Energy Chronology: 1980-April 2005" Energy Information Administration, Country Analysis Briefs – Iraq: Chronology. Retrieved from http://www.eia.doe.gov/emeu/cabs/iraqchron.html on 10 June 2005. June.

GAMS Development Corp, 2003, GAMS v2.029.8. Software available from www.gams.com. Retrieved August 2005.

Gates, Robert M., 1985, “The Iran-Iraq War: Some Oil Vulnerability Issues”, Deputy Director of Intelligence. An intelligence assessment provided to VADM John Poindexter, Deputy Asst. to the President for National Security Affairs. Declassified April 2002. 13 September. 17 pages.

Ghosh, Amitava, 2005a, “Facilities Unit Costs - Military Construction”, Pax Newsletter (3.2.2). Headquarters, U.S. Army Corps of Engineers. Provided via email from author 15 July 2005. Available online at http://www.hq.usace.army.mil/cemp/e/ec/PAX/paxtoc.htm. 15 March. 21 pages.
Updates the Appendix A, Facility Unit Cost Table, Appendix C, Tri-Service Military Construction Program (MCP) Index, and Table 1, Size Adjustment Factors, contained in TM 5-800-4, Programming Cost Estimates for Military Construction, dated May 1994.

Ghosh, Amitava, 2005b, “Area Cost Factor (ACF) Indexes”, Pax Newsletter (3.2.1). Headquarters, U.S. Army Corps of Engineers. Provided via email from author 27 July 2005. Available online at http://www.hq.usace.army.mil/cemp/e/ec/PAX/paxtoc.htm. January. 16 pages.
Supercedes the ACF list published by the PAX Newsletter, dated 23 December 2003, and Appendix B of the current Army Technical Manual TM 5-800-4, Programming Cost Estimates for Military Construction (MILCON), dated May 1994. 31

Giragosian, Richard, 2004, “Targeting Weak Points: Iraq's Oil Pipelines”, Radio Free Europe/Radio Liberty as reprinted on Asia Times Online. Retrieved from http://www.atimes.com/atimes/Middle_East/FA27Ak03.html on 5 July 2005. 27 January.

Greste, Peter, 2004, “Protecting Iraq’s Oil Infrastructure”, BBC News World Edition (online): Middle East. Retrieved from http://news.bbc.co.uk/2/hi/middle_east/3526016.stm on 6 October 2004. 3 August.

Institute for the Analysis of Global Security (IAGS), 2005, “Iraq Pipeline Watch”, IAGS: Energy Security. Retrieved from http://www.iags.org/iraqpipelinewatch.htm on 16 Jun 2005.

ILOG. 2004. CPLEX 9.0. Retrieved from http://www.cplex.com on 10 Sep 2005.

Kennedy, Tim, 2004, “Saudi Oil Is Secure and Plentiful, Say Officials”, Arab News. Retrieved from http://www.arabnews.com/?page=6&section=0&article=44011&d=29&m=4&y=2004 on 23 Jun 2005. 29 April.

Klare, Michael T., 2004, “The Oil That Drives the US Military”, article first appeared at TomDispatch (http://www.tomdispatch.com/) and published online at Asia Times Online (http://www.atimes.com/) and others. Retrieved from http://www.atimes.com/atimes/Global_Economy/FJ09Dj01.html on 18 July 2005. 9 October.
***Michael Klare** is a professor of peace and world security studies at Hampshire College. This article is based on his new book,* Blood and Oil: The Dangers and Consequences of America's Growing Petroleum Dependency *(Metropolitan/Henry Holt).*

Luft, Gal, 2004, “Iraq's Oil Sector One Year After Liberation”, Bookings Institute: Foreign Policy Studies: Saban Center for Middle East Policy. Middle East Memo #4. Retrieved from http://www.brookings.edu/fp/saban/luftmemo20040617.htm on 6 October 2004. 17 June.
Gal Luft is the Co-Director, Institute for the Analysis of Global Security (IAGS).

McFall, Kathleen, 2003, “Post-9/11 Investigations Reveal Oil, Gas Achilles Heel”, ENR (Engineering News-Record), 250(9), 11. Retrieved from http://www.construction.com/NewsCenter/Headlines/ENR/20030307b.asp on 18 July 2005. 10 March.

McKillop, Andrew, 2004, “Oil Prices, Economic Growth and World Oil Demand”, Alexander’s Gas and Oil Connections: Commentary and Analysis, Speeches. Retrieved from http://www.gasandoil.com/goc/speeches/mckillop.htm. on 18 January 2005.

Mehr, 2005, “Iran, Iraq to Construct Swap Oil Pipeline: Zanganeh”, MehrNews.Com, Mehr News Agency. Retrieved from http://www.mehrnews.ir/en/NewsDetail.aspx?NewsID=203086 on 20 August 2005. 4 July.

Montgomery, Douglas C., Peck, Elizabeth A, and Vining, Geoffrey G, 2001, *Introduction to Linear Regression Analysis* (3rd ed.), New York: John Wiley & Sons, Inc.

Payvand, 2005, “Iran-Iraq Oil Pipeline to Become Operational Next Year”, Payvand’s Iran News Service. Retrieved from http://www.payvand.com/news/05/jul/1148.html on 20 August 2005. 18 July.

Peat, Chris, 2005, Heavens-Above, Available online at http://www.heavens-above.com. *Used as a resource for identifying latitudes and longitudes for common location in Iraq. Chris Peat is the maintainer of the database used by the website.*

SPG Media Limited, 2005, “Hydrocarbons Technology: Baku-Tbilisi-Ceyhan (BTC) Caspian Pipeline”, subsidiary of SPG Media Group PLC. Retrieved from http://www.hydrocarbons-technology.com/projects/bp/ on 31 August 2005. 3 August.

U.S. Army, 1994, “Programming Cost Estimates for Military Construction”, Technical Manual 5-800-4, Headquarters, Department of the Army, 25 May, 79 pages.

U.S. Navy, 2005, “NCAD Inflation Indices: FY06 Inflation Calculator,” Navy Cost and Analysis Division (NCAD). Retrieved from http://www.ncca.navy.mil/services/Inflation_Calc_FY06_Ver_2.xls on 19 July 2005. April.

Wikipedia, 2005, “Trans-Afghanistan Pipeline” Wikipedia Online. Retrieved from http://en.wikipedia.org/wiki/Trans-Afghanistan_Pipeline on 25 August 2005. August.

Wood, K., 1993, “Deterministic Network Interdiction,” *Mathematical and Computer Modeling*, 17, pp. 1-18.

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

3. Professor Gerald Brown
   Naval Postgraduate School
   Monterey, California

4. Associate Professor Curt Blais
   Naval Postgraduate School
   Monterey, California

5. Professor Dan Nussbaum
   Naval Postgraduate School
   Monterey, California

6. LCDR Shane Brown
   Naval Postgraduate School
   Monterey, California